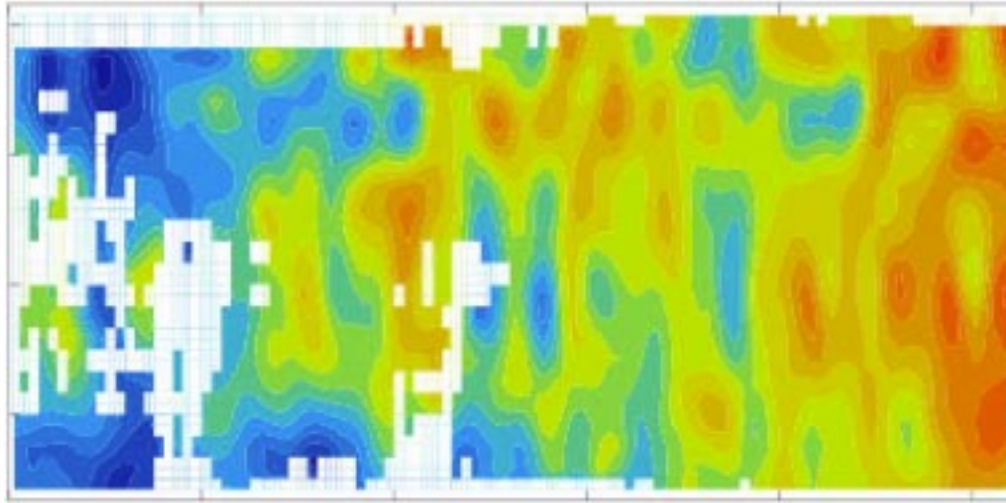


# DOING SOMETHING ABOUT THE CLIMATE: GREENHOUSE GASES, AEROSOLS, RADIATIVE FORCING, AND IMPLICATIONS



Stephen E. Schwartz

Environmental Sciences Department BNL

*Physics Colloquium, BNL*

November 8, 2005

<http://www.ecd.bnl.gov/steve/schwartz.html>

*Everybody talks about the weather —*

*But nobody does anything about it.*

*– Mark Twain*

# QUESTIONS ABOUT CLIMATE CHANGE

Are atmospheric CO<sub>2</sub> and other greenhouse gases increasing?

Why?

What human or other activities are responsible?

Is Earth's temperature increasing?

Why?

Can temperature increase be quantitatively understood and related to causes?

What future temperature increases (and other climate changes) can be expected?

What is the uncertainty?

What is the “take-home” message regarding present understanding of climate change?

# OUTLINE

Radiative fluxes and radiative forcing of climate change

Radiative forcing of climate change

Trends in carbon dioxide and temperature

Attribution of excess atmospheric carbon dioxide

Climate sensitivity

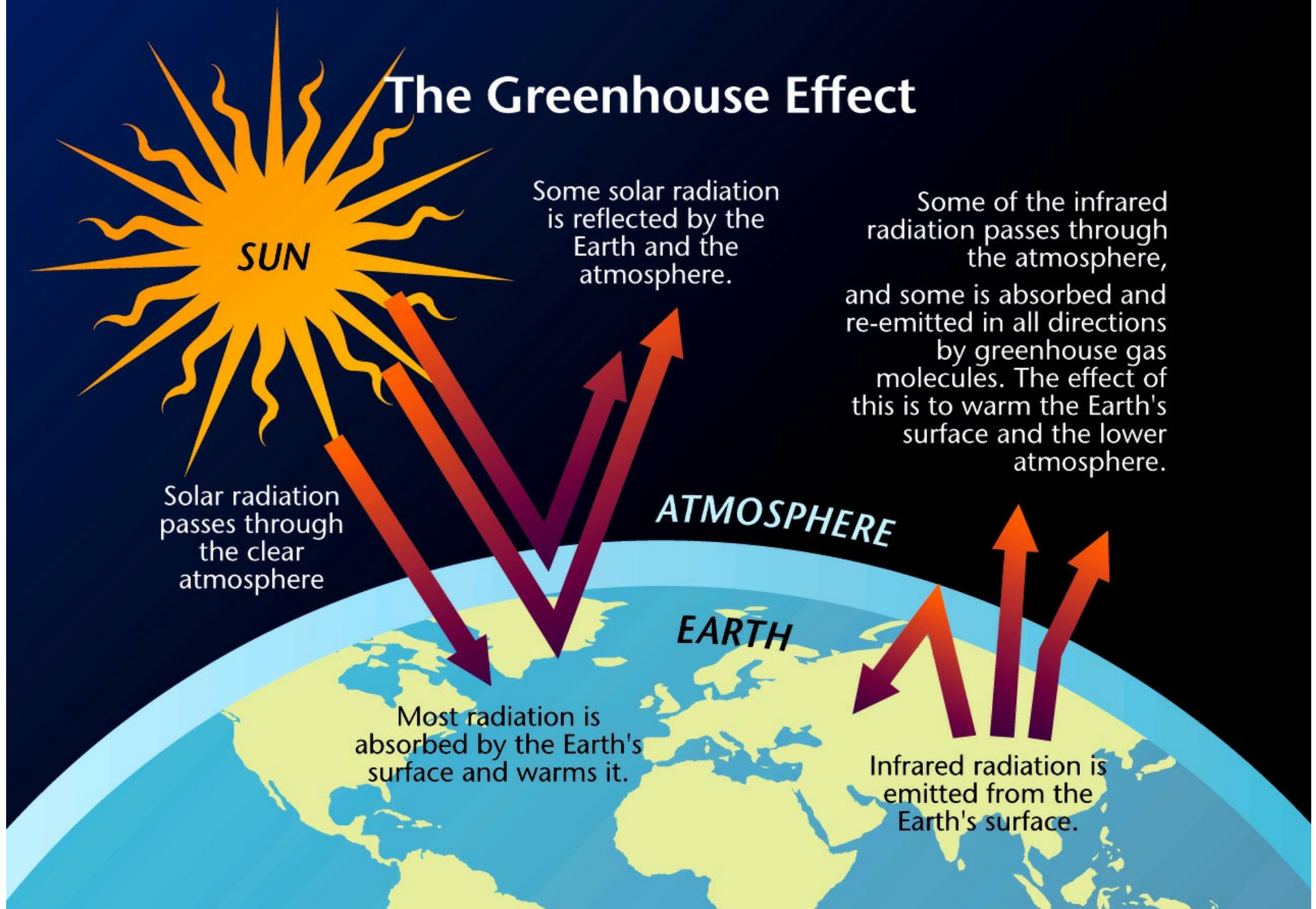
Time constant of climate change

Radiative forcing by aerosols

Radiative forcing over the industrial period and its uncertainty

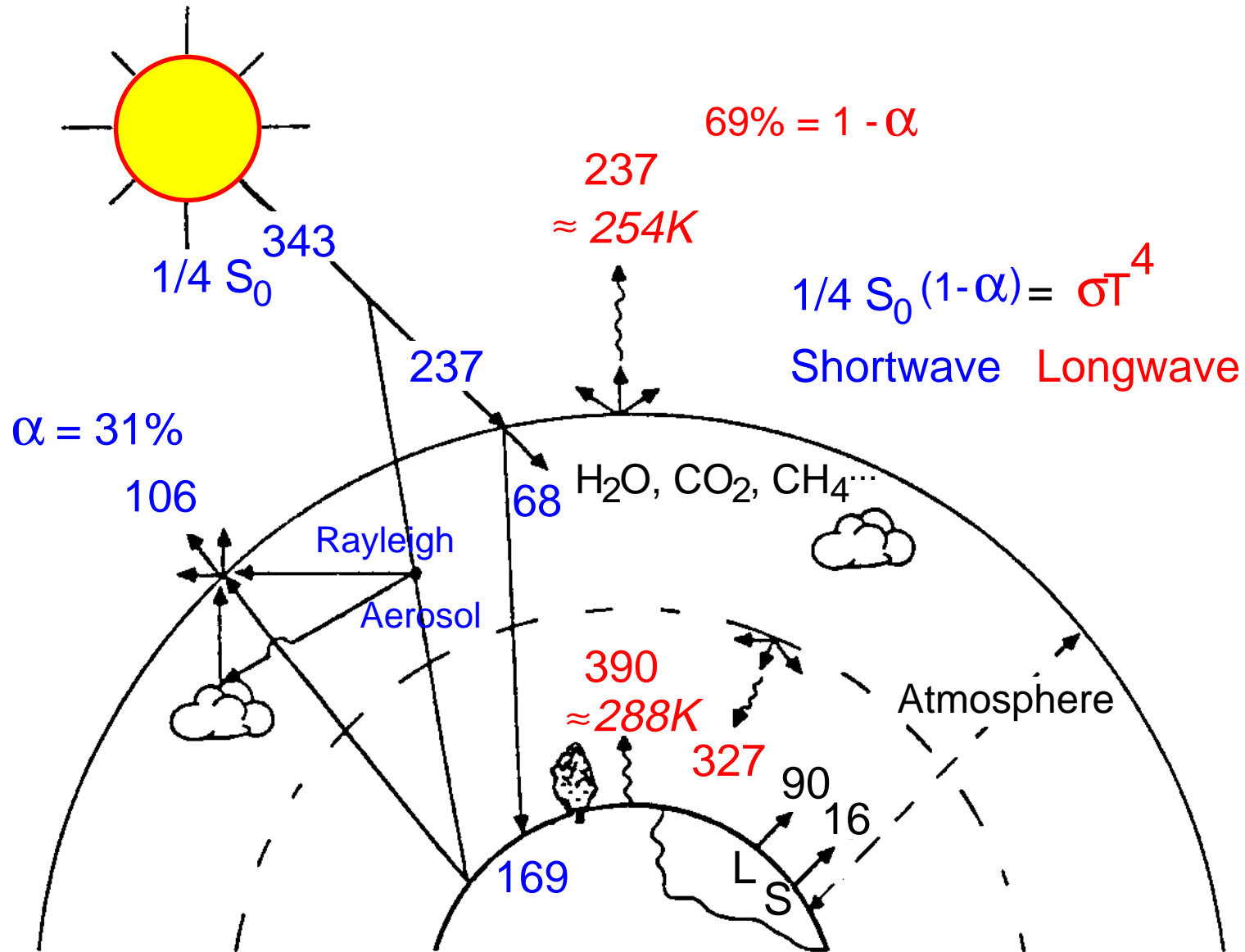
Concluding remarks

# The Greenhouse Effect



# GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



*Schwartz, 1996, modified from Ramanathan, 1987*



# ***ATMOSPHERIC RADIATION***

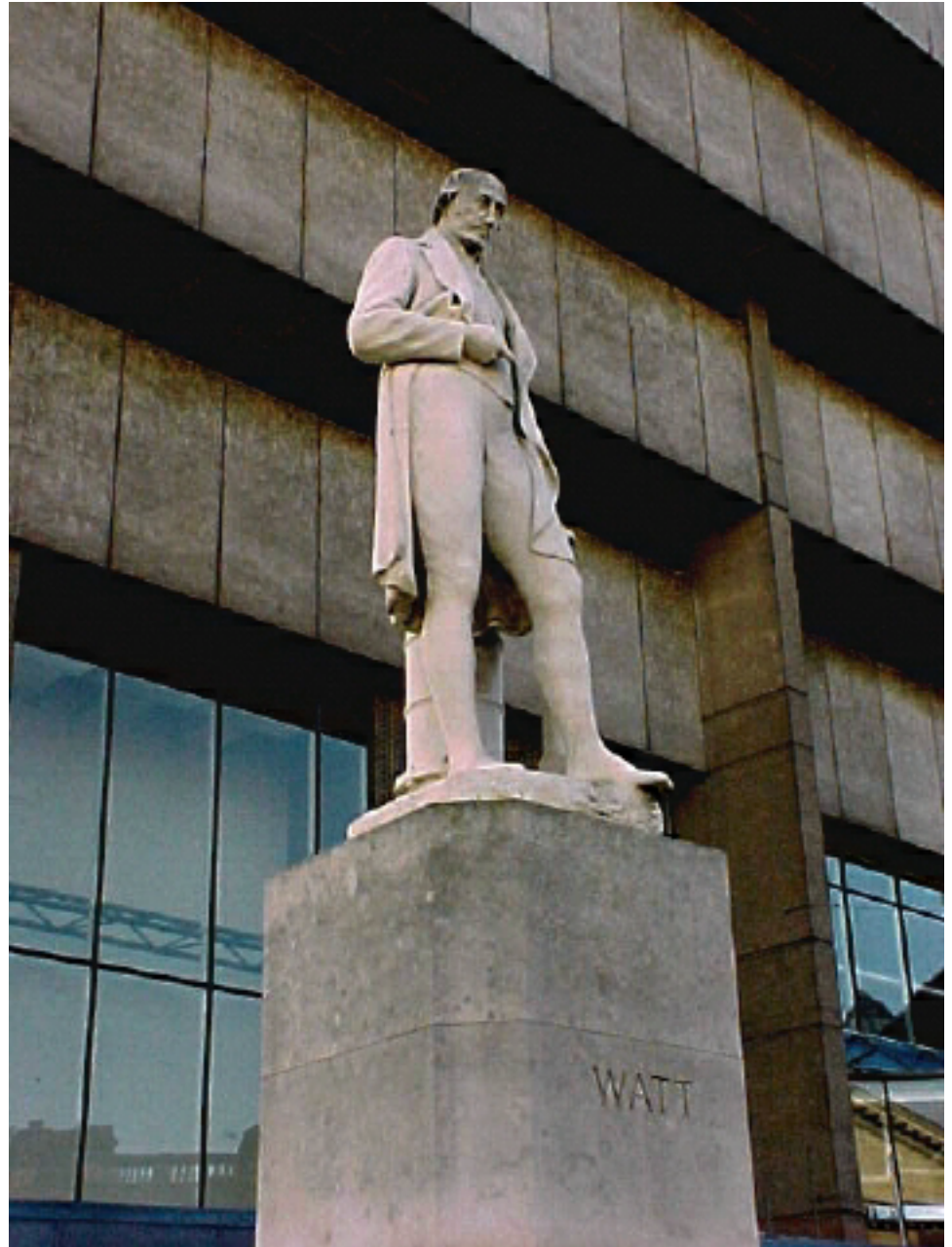
***Energy per area per  
time***

***Power per area***

***Unit:***

***Watt per square meter***

***$W m^{-2}$***

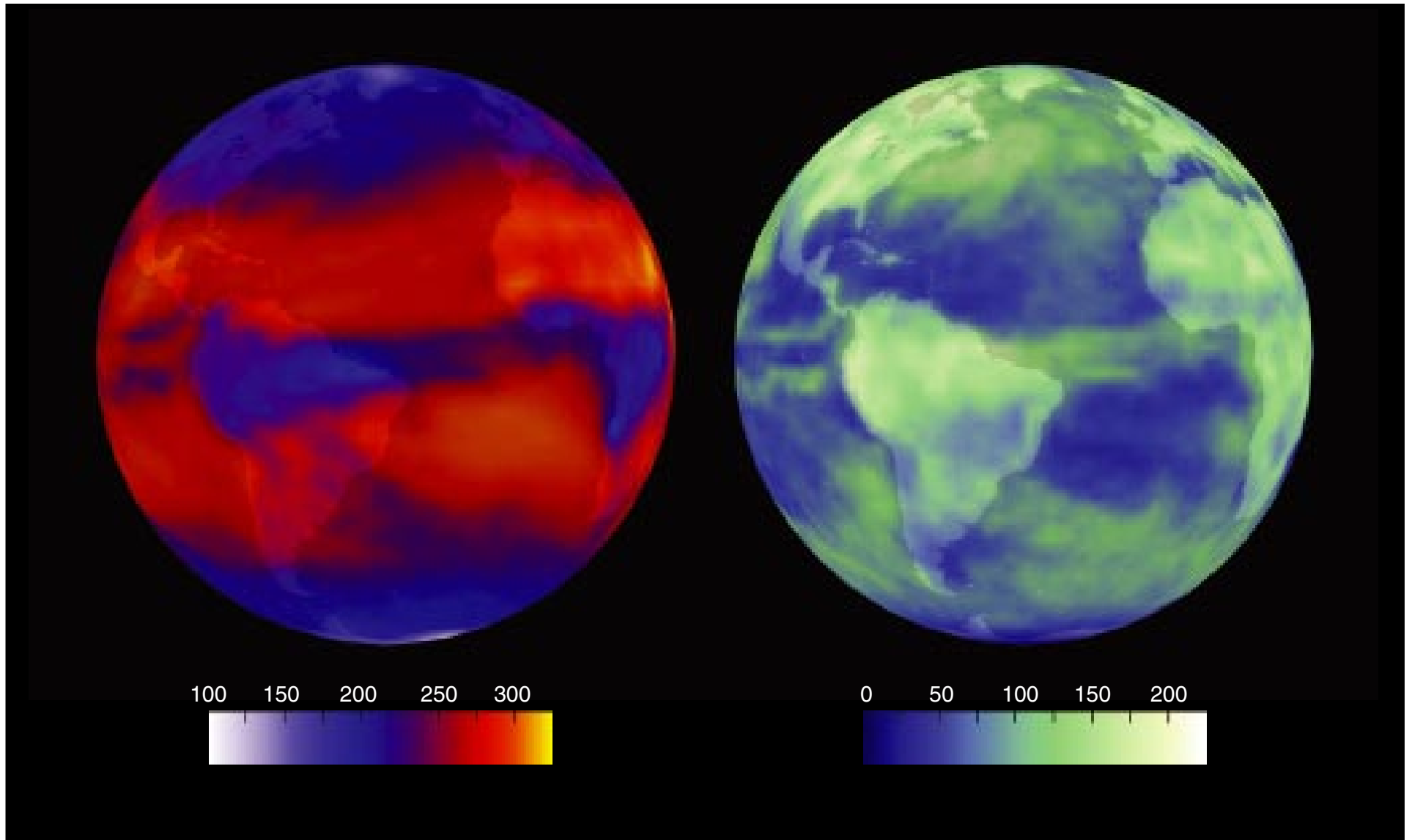


# GEOGRAPHICAL VARIATION OF ATMOSPHERIC RADIATION

Annual average radiative flux at top of atmosphere,  $\text{W m}^{-2}$

Emitted thermal infrared

Reflected shortwave



CERES (Clouds and Earth's Radiant Energy System satellite, March, 2000 - May, 2001



# ***RADIATIVE FORCING OF CLIMATE CHANGE***

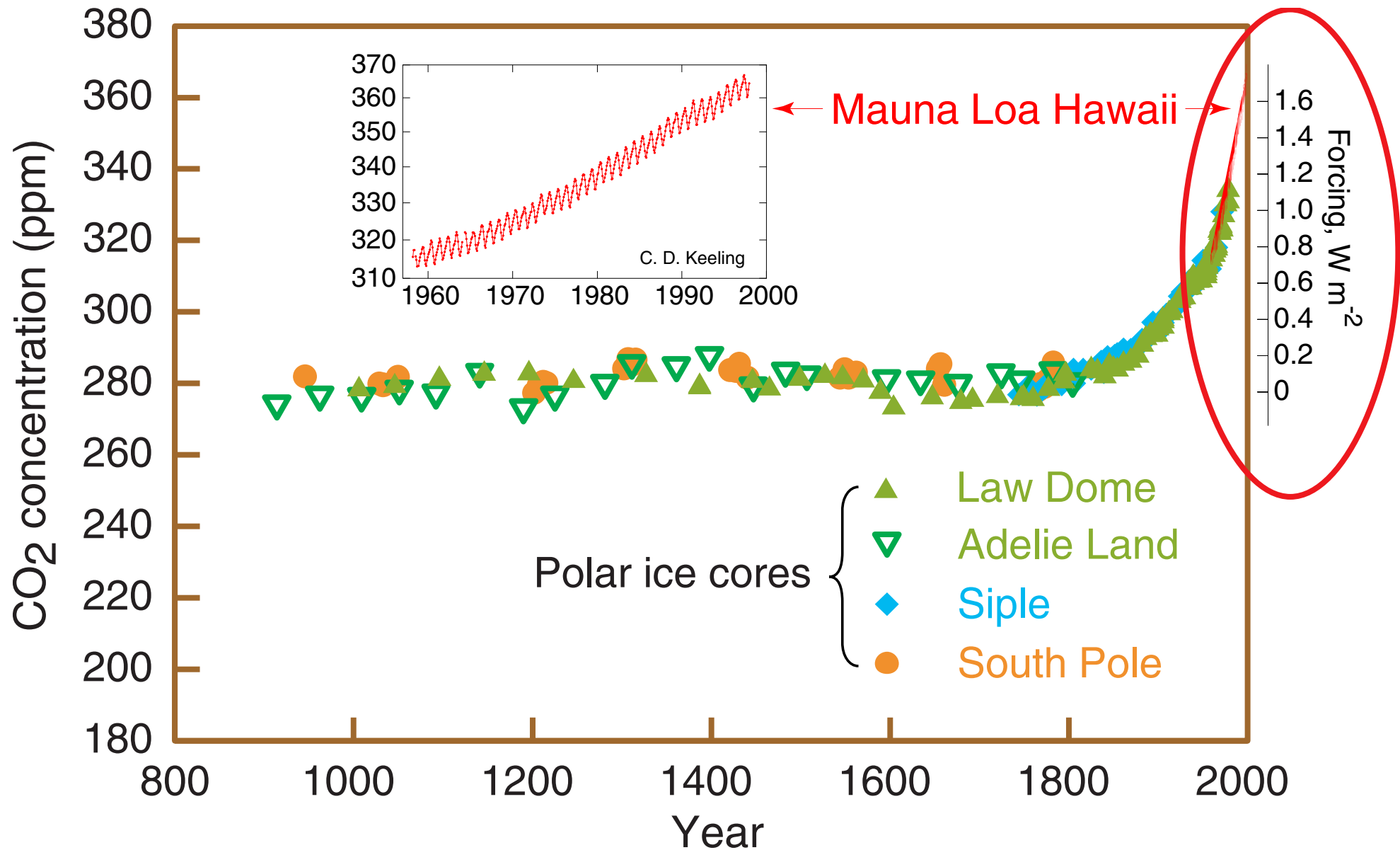
A ***change*** in a radiative flux term in the Earth's radiation budget,  $\Delta F$ ,  $\text{W m}^{-2}$ .

***Working hypothesis:***

*On a global basis radiative forcings are **additive** and **fungible**.*

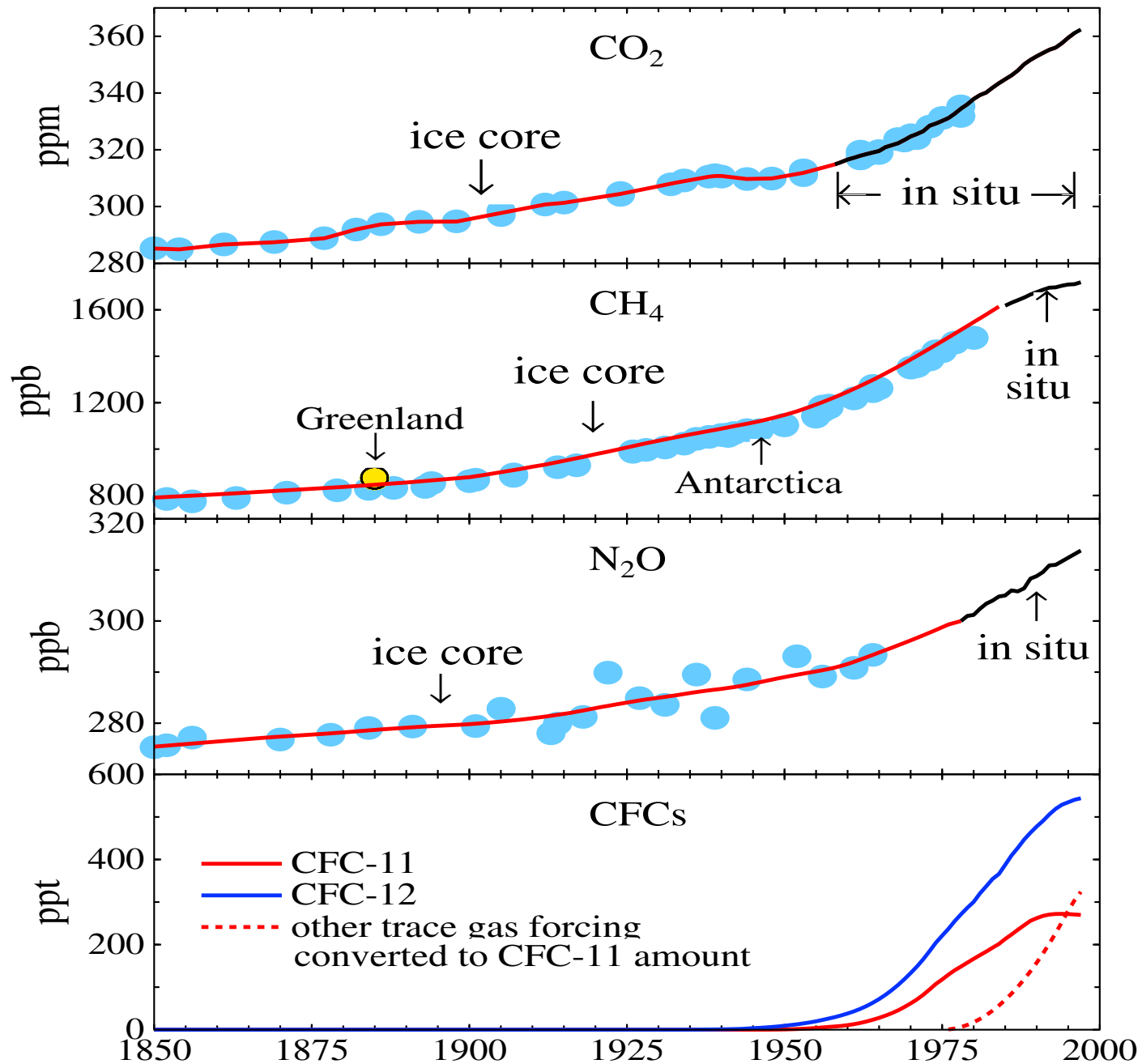
The radiative forcing concept underlies much of the assessment of climate change over the industrial period.

# ATMOSPHERIC CARBON DIOXIDE IS INCREASING



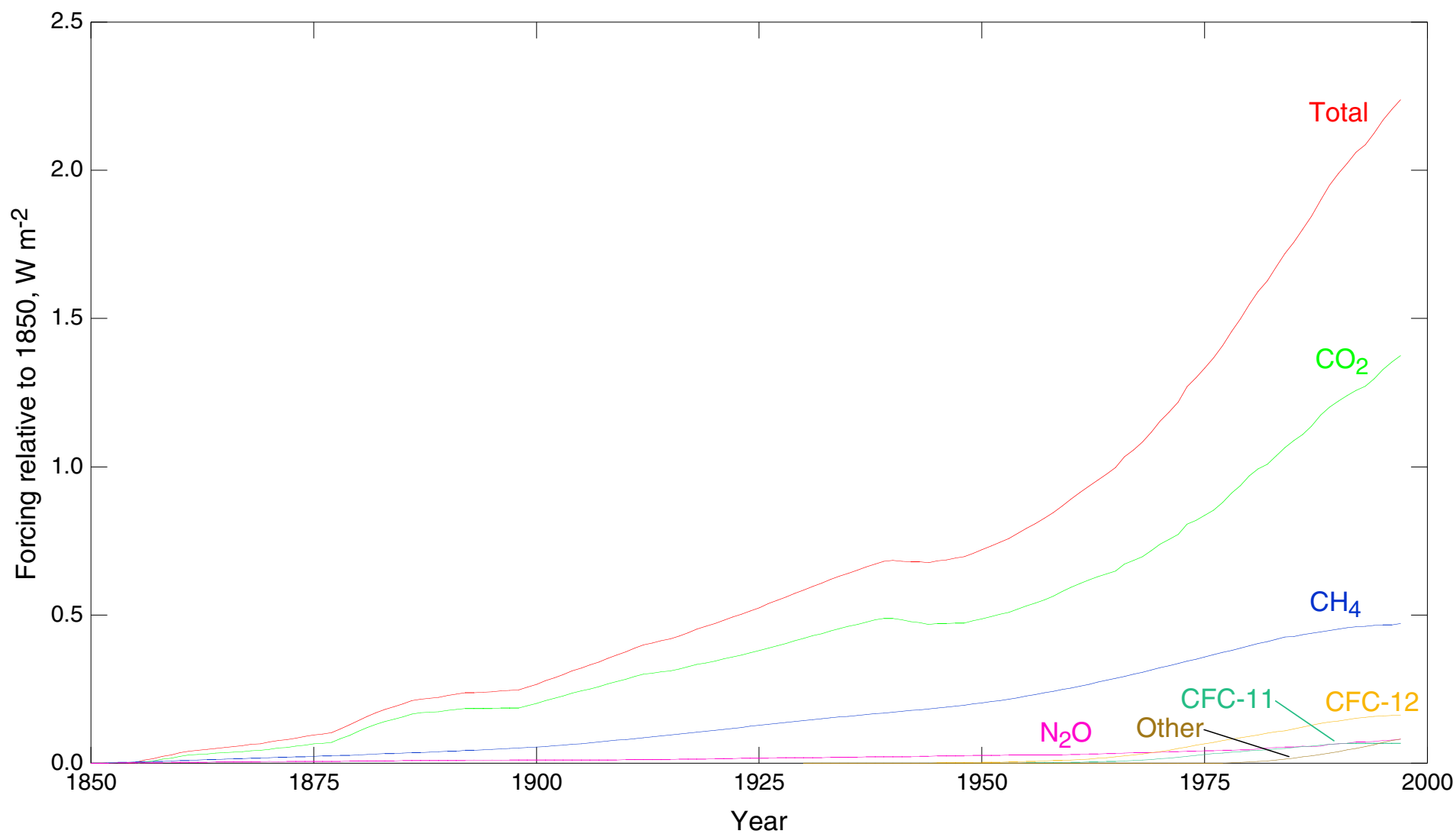
Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

# GREENHOUSE GAS MIXING RATIOS OVER THE INDUSTRIAL PERIOD



Hansen *et al.*, PNAS. 1998

# GREENHOUSE GAS FORCINGS OVER THE INDUSTRIAL PERIOD

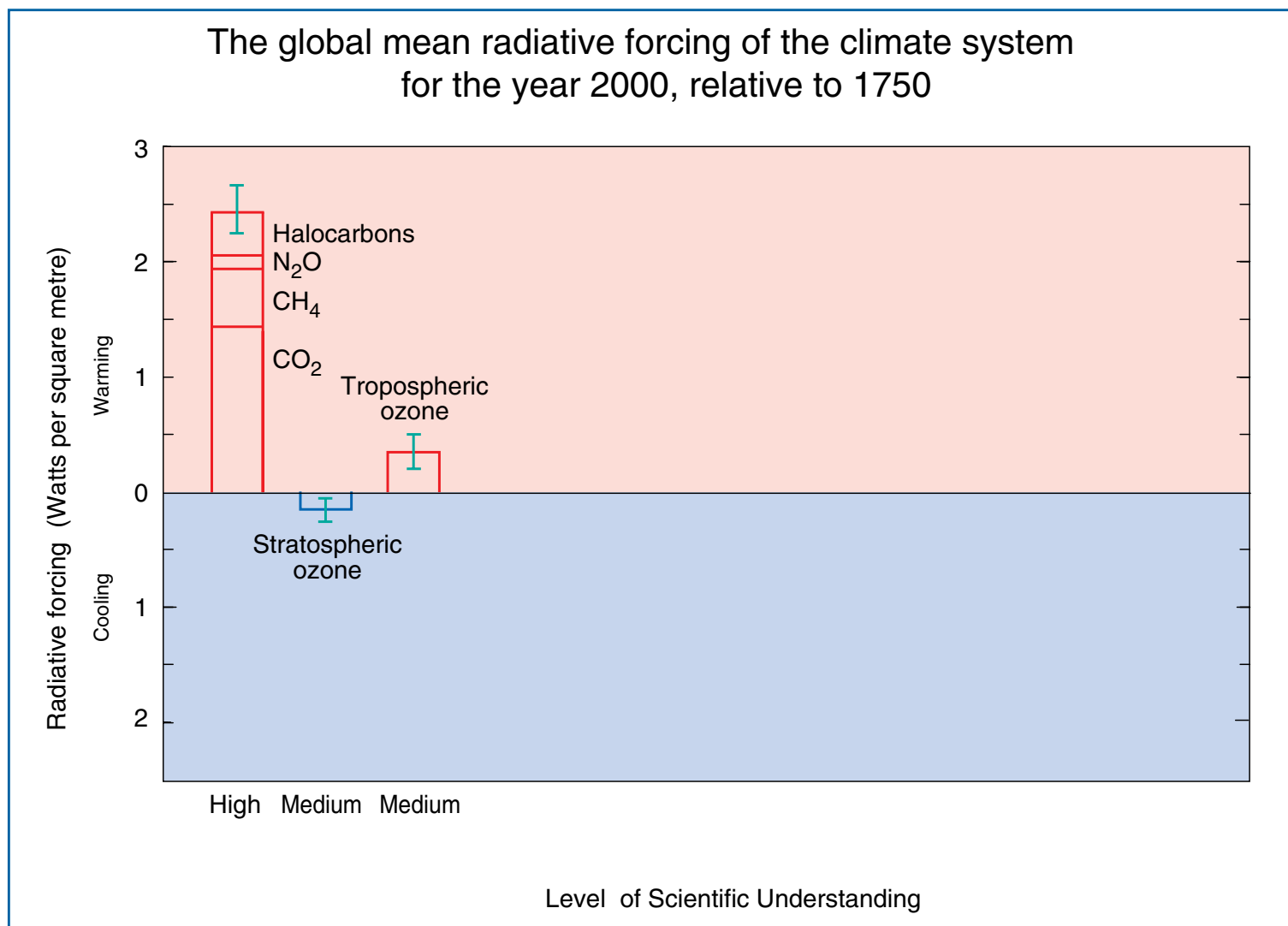


Data: GISS

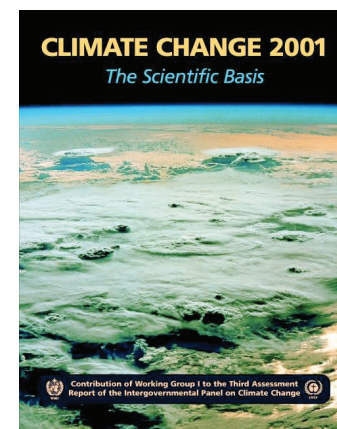
# RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD

## IPCC (2001)

### Greenhouse gases



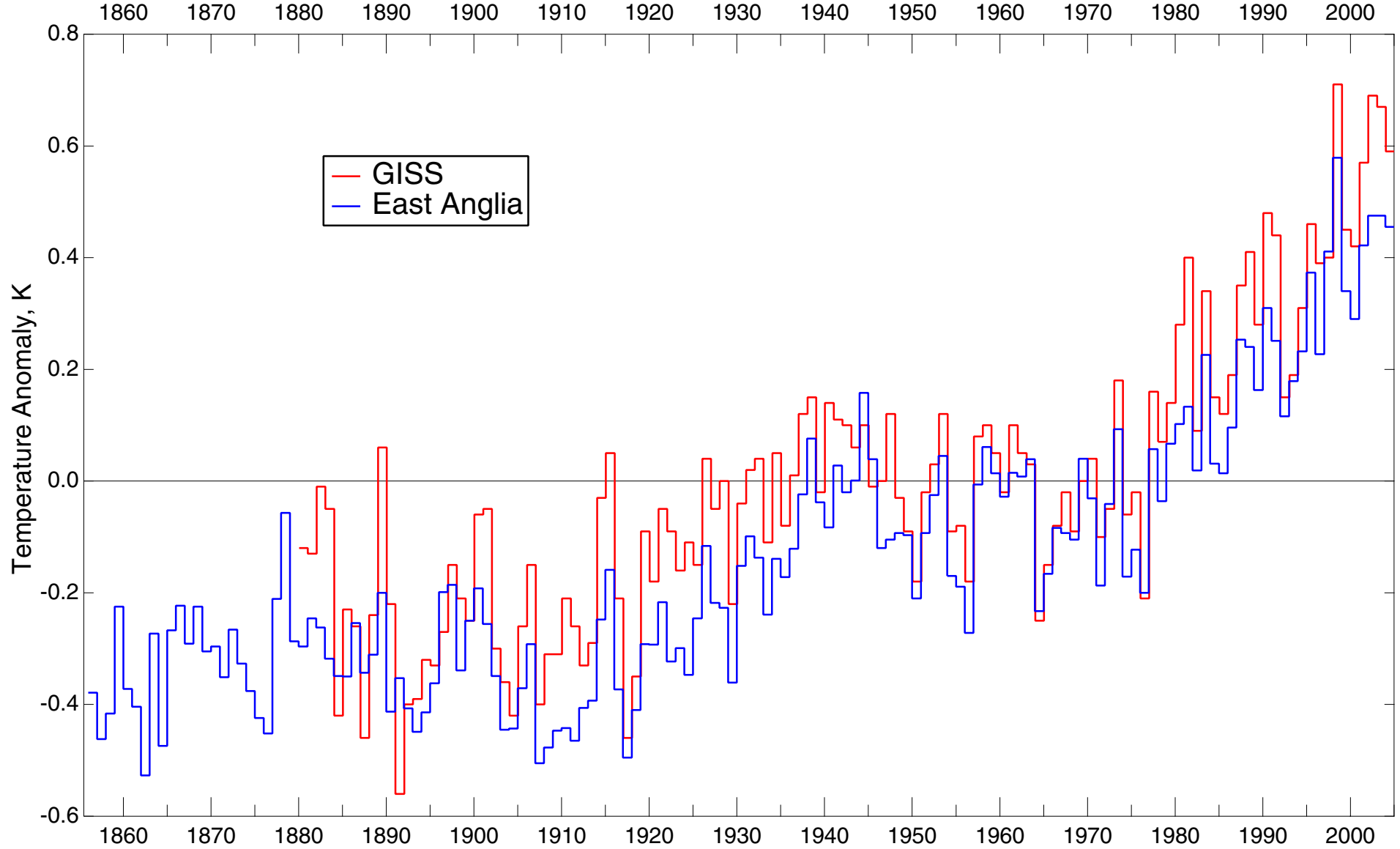
Summary for Policymakers A Report of Working Group I of the Intergovernmental Panel on Climate Change



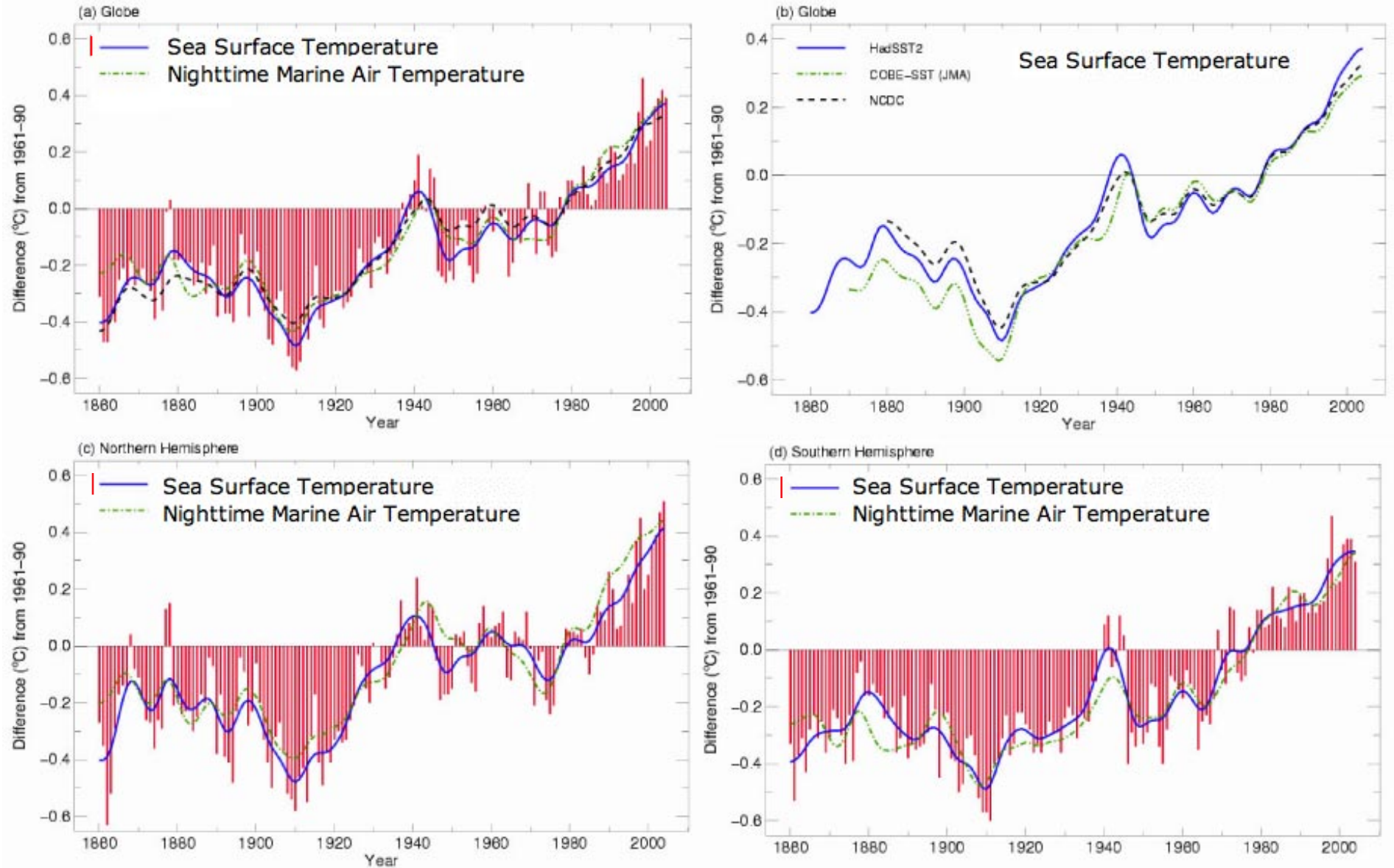


IS EARTH'S TEMPERATURE  
INCREASING?

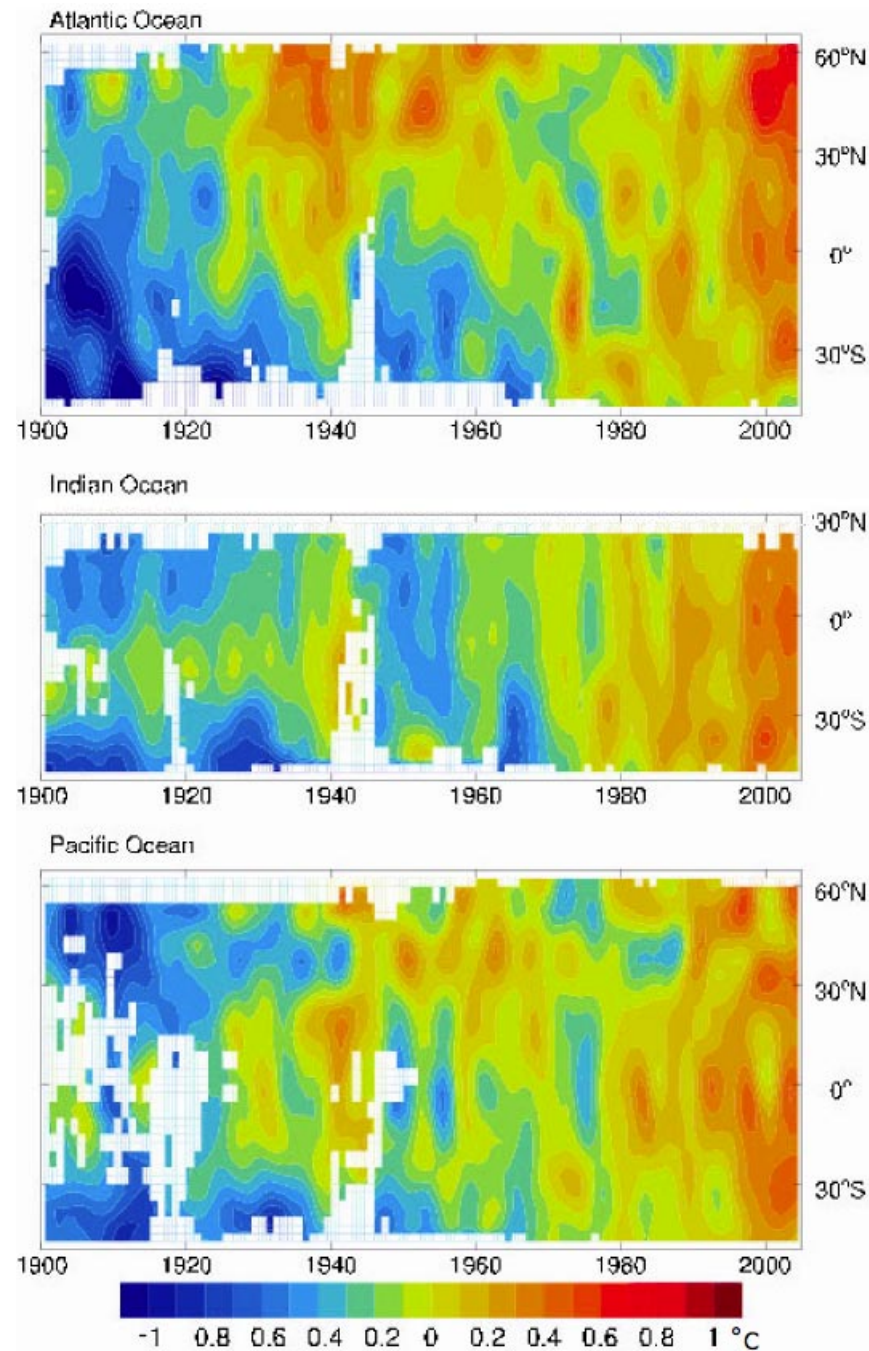
# GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



# OCEAN SURFACE TEMPERATURE ANOMALY



# OCEAN SURFACE TEMPERATURE ANOMALY



# RETREAT OF MID-LATITUDE GLACIERS

## South Cascade Glacier, Washington

1928



2000

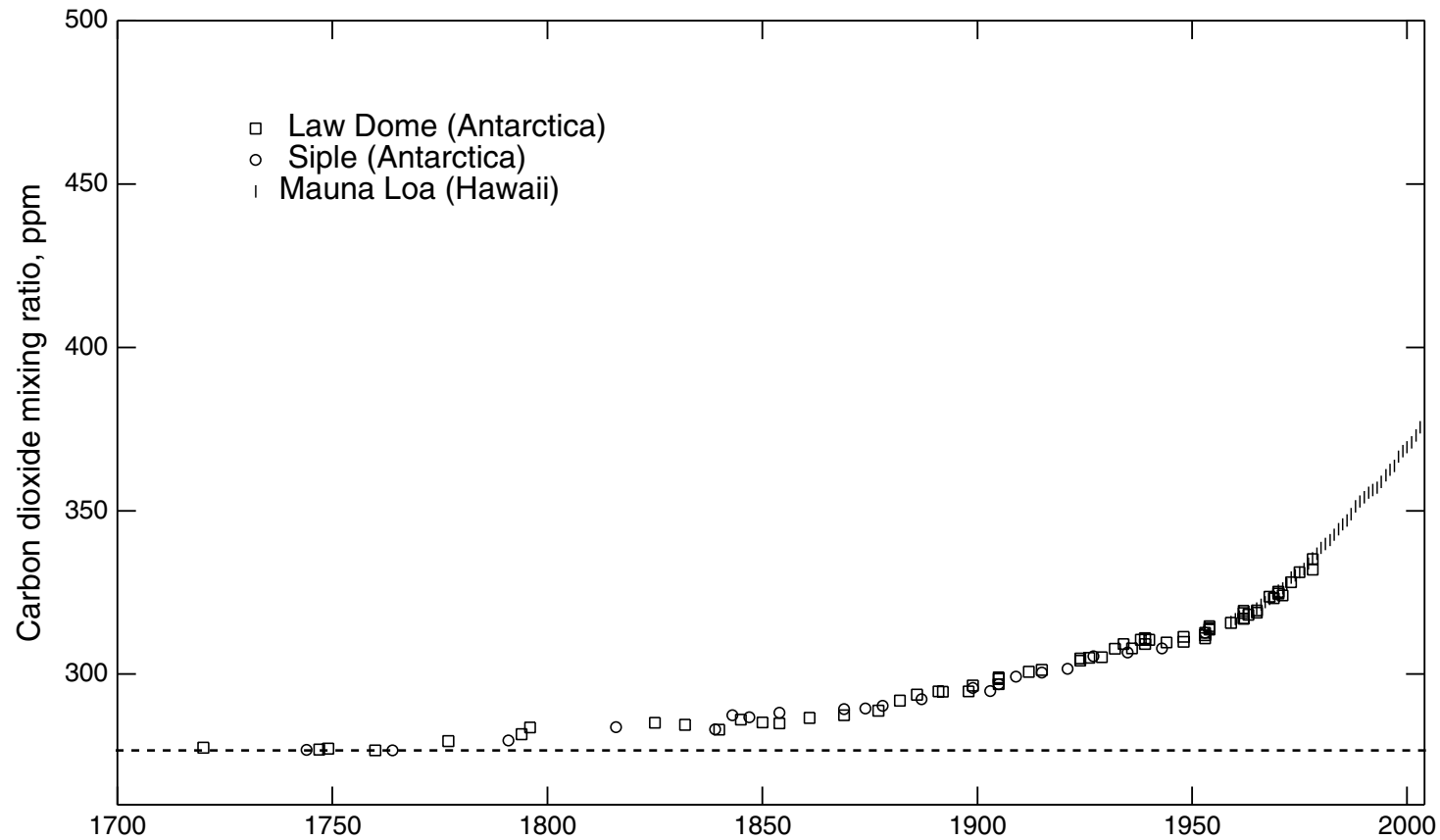




# INCREASES IN CO<sub>2</sub> OVER THE INDUSTRIAL PERIOD

# ATMOSPHERIC CARBON DIOXIDE

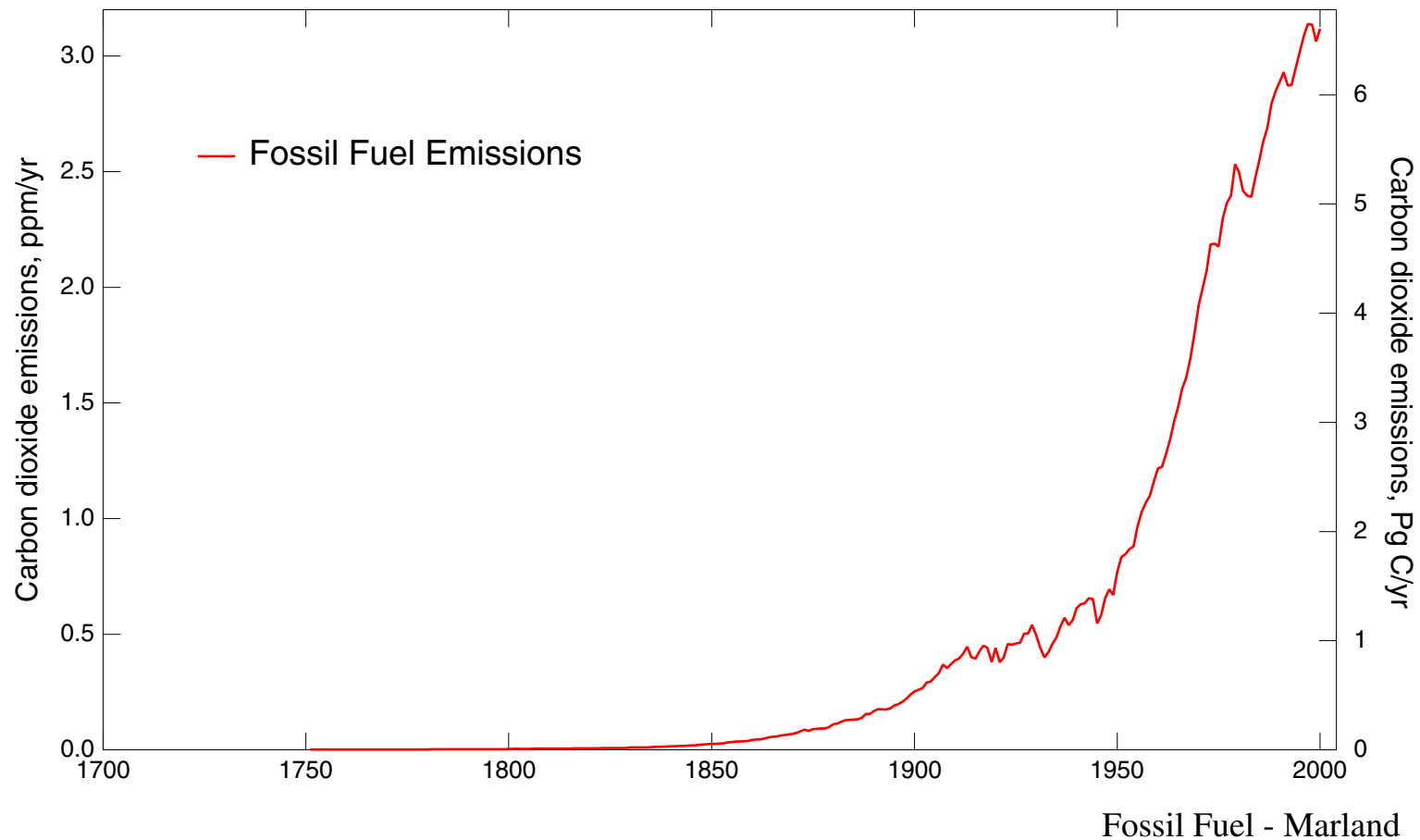
## Time series 1700 - 2003



Law - Etheridge et al.  
Siple - Friedli et al.  
Mauna Loa - Keeling

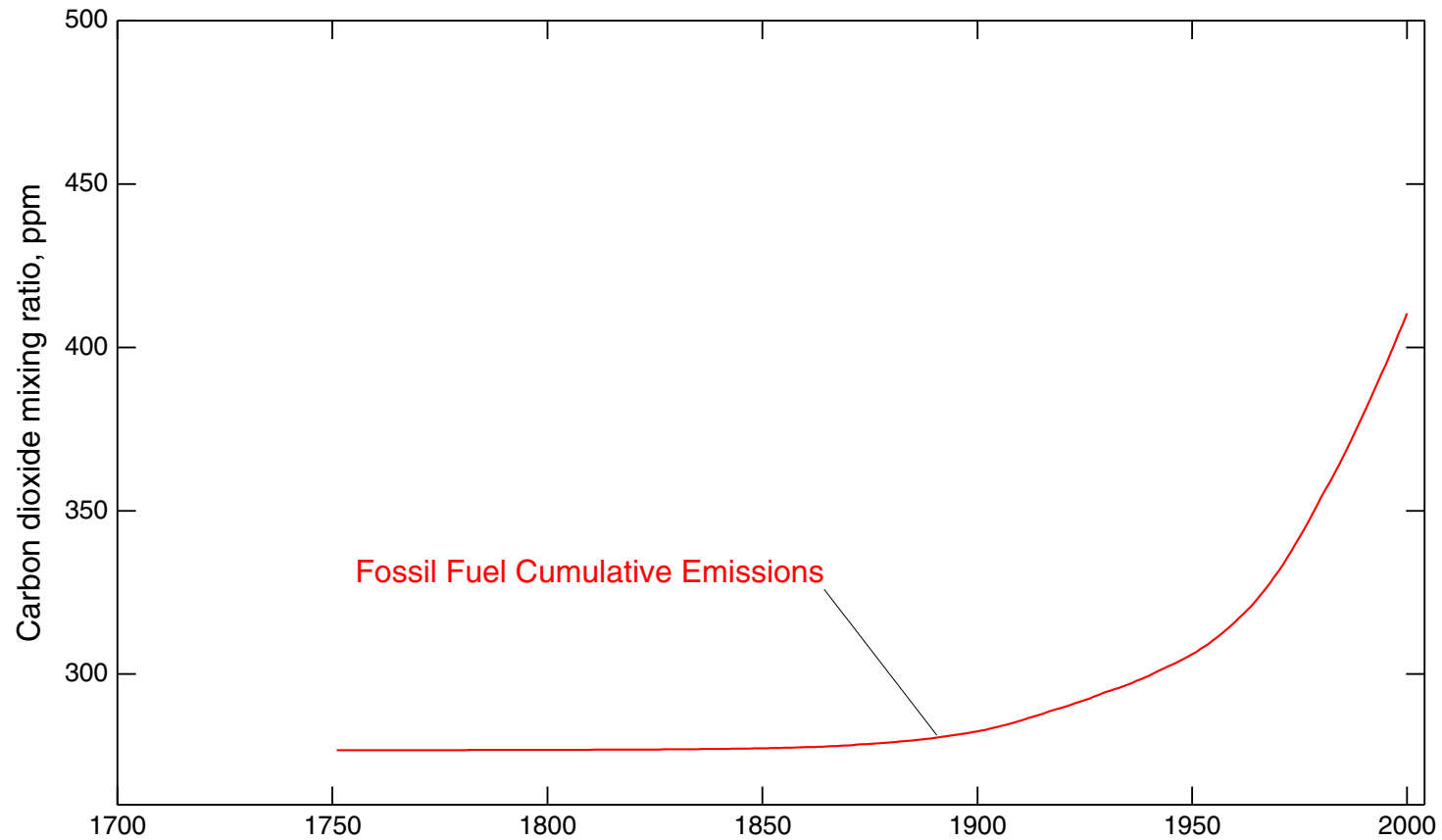
# ATMOSPHERIC CO<sub>2</sub> EMISSIONS

## Time series 1700 - 2003



# ATMOSPHERIC CARBON DIOXIDE

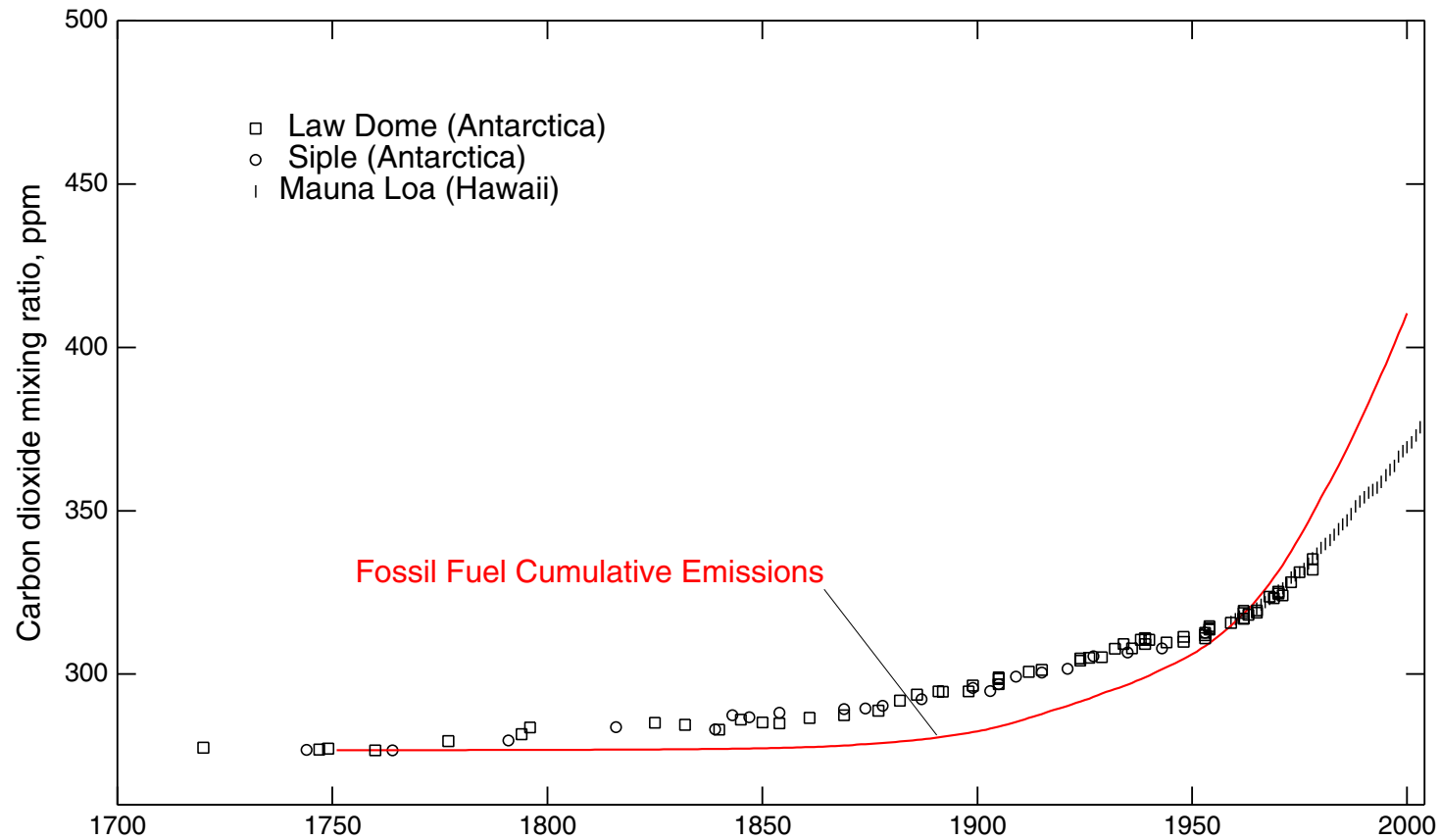
## Time series 1700 - 2003



Fossil Fuel - Marland

# ATMOSPHERIC CARBON DIOXIDE

## Time series 1700 - 2003

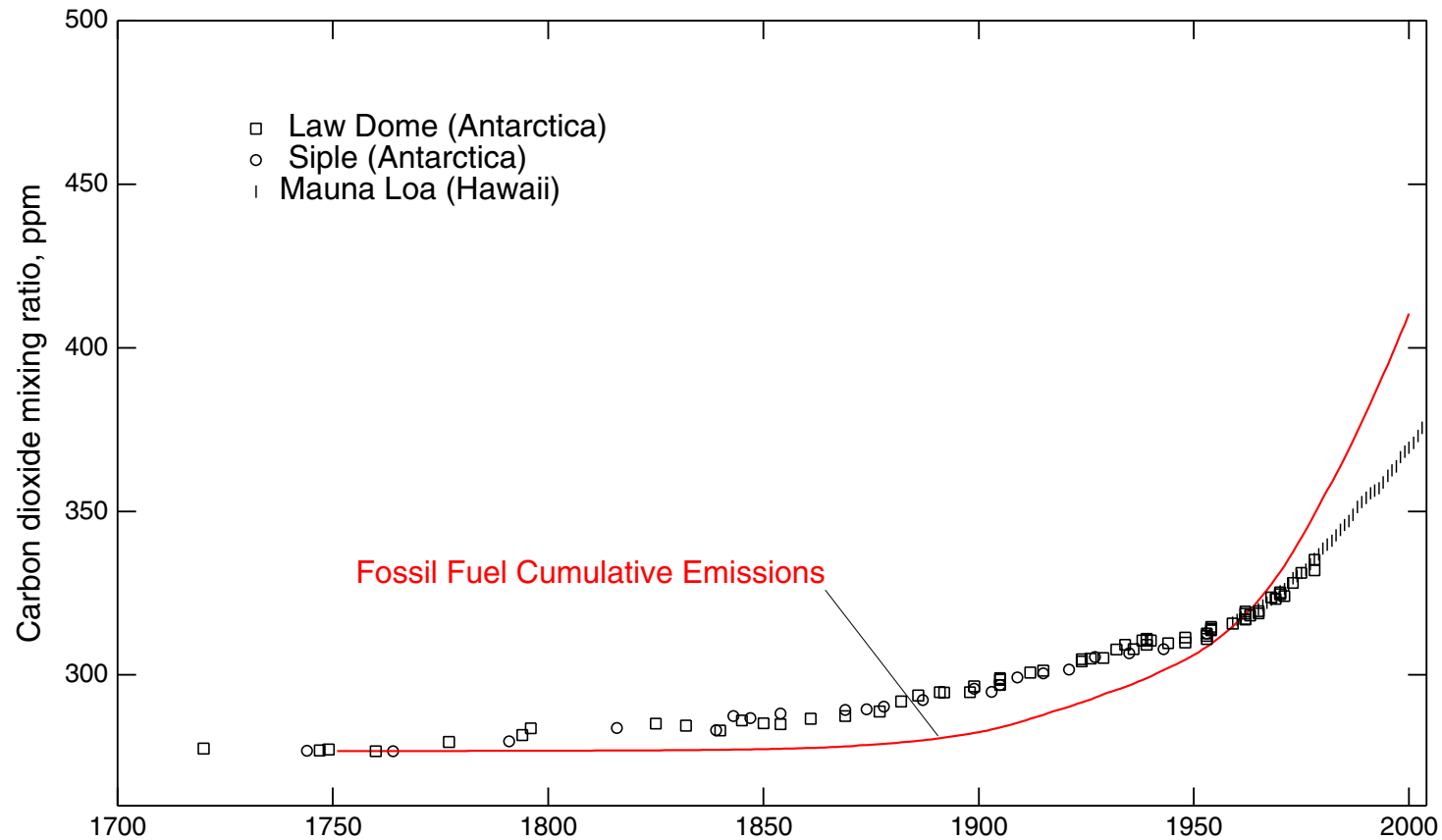


Law - Etheridge et al.  
Siple - Friedli et al.  
Mauna Loa - Keeling  
Fossil Fuel - Marland



# ATMOSPHERIC CARBON DIOXIDE

## Time series 1700 - 2003



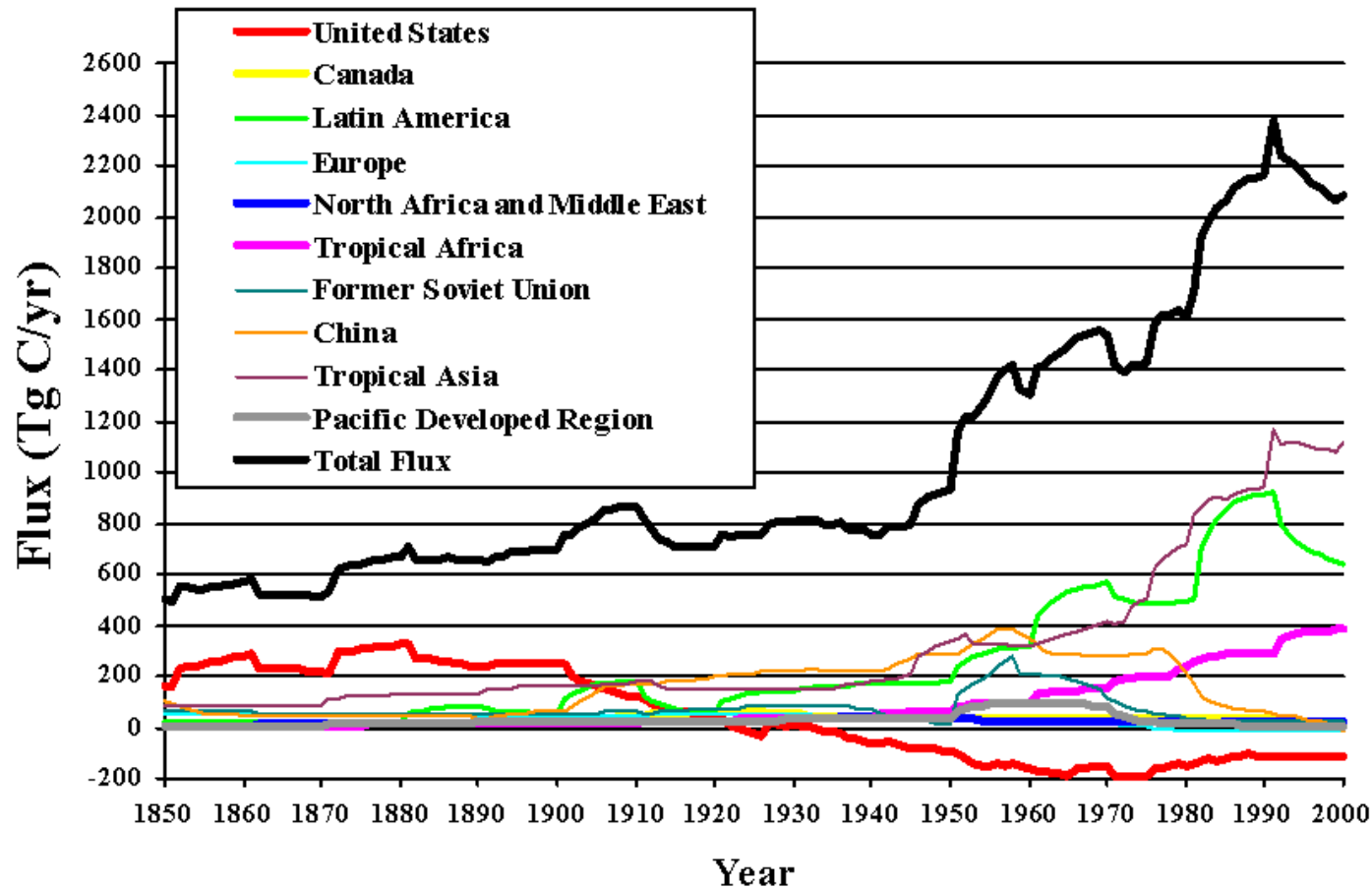
Law - Etheridge et al.  
Siple - Friedli et al.  
Mauna Loa - Keeling  
Fossil Fuel - Marland

*What's missing?*

# LAND USE CARBON EMISSIONS BY SOURCE REGION

Annual Net Flux of Carbon to the Atmosphere from Land-Use Change: 1850-2000

(Houghton and Hackler)



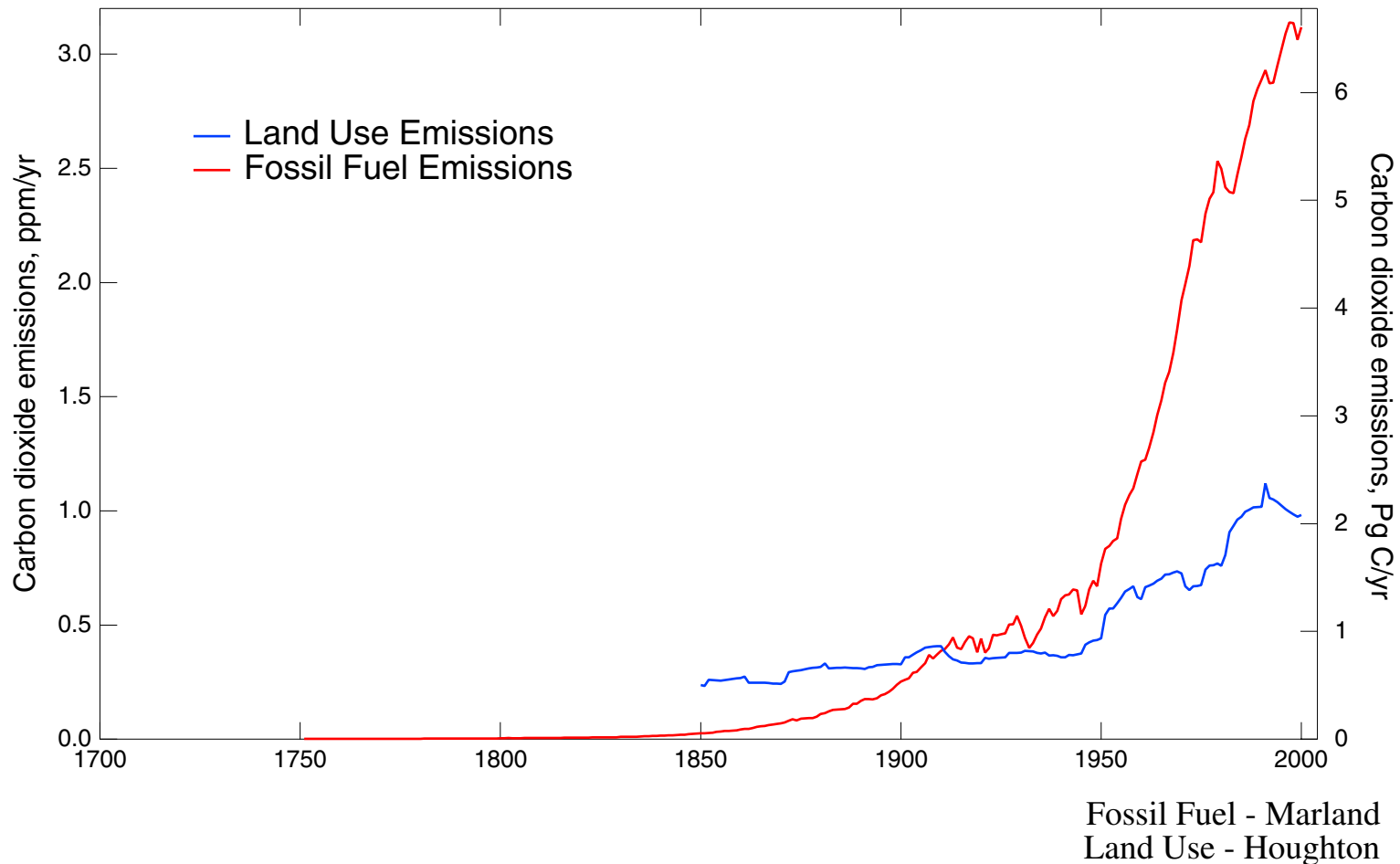
1000 Tg = 1 Pg  
=  $10^{15}$  g,  
Equivalent to  
0.47 ppm

Carbon flux estimated as land area times carbon emissions associated with deforestation (or uptake associated with afforestation).

United States dominates emissions before 1900 and uptake after 1940.

# ATMOSPHERIC CO<sub>2</sub> EMISSIONS

## Time series 1700 - 2003

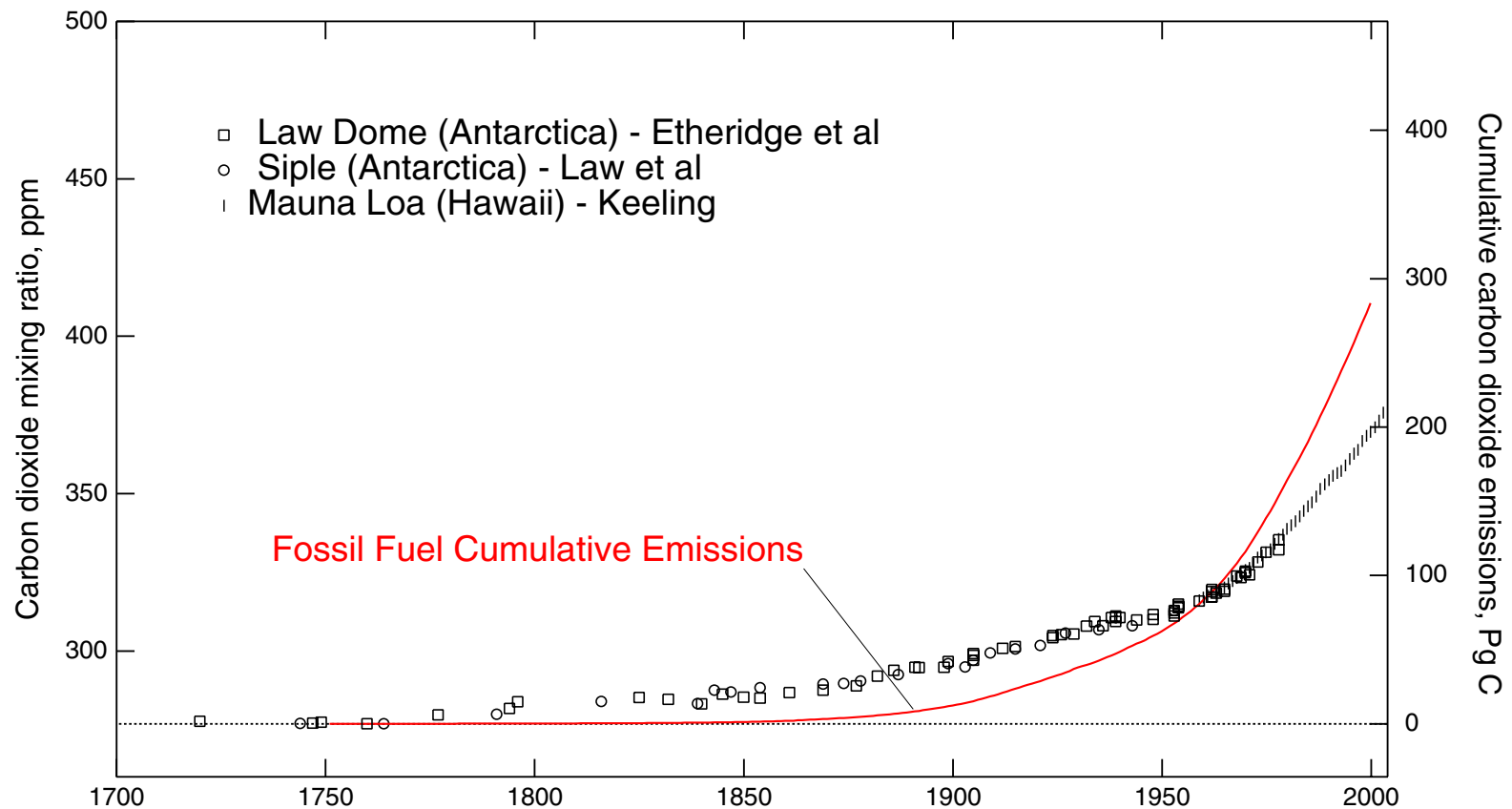


*Prior to 1910 CO<sub>2</sub> emissions from land use changes were dominant.*

*Subsequently fossil fuel CO<sub>2</sub> has been dominant and rapidly increasing!*

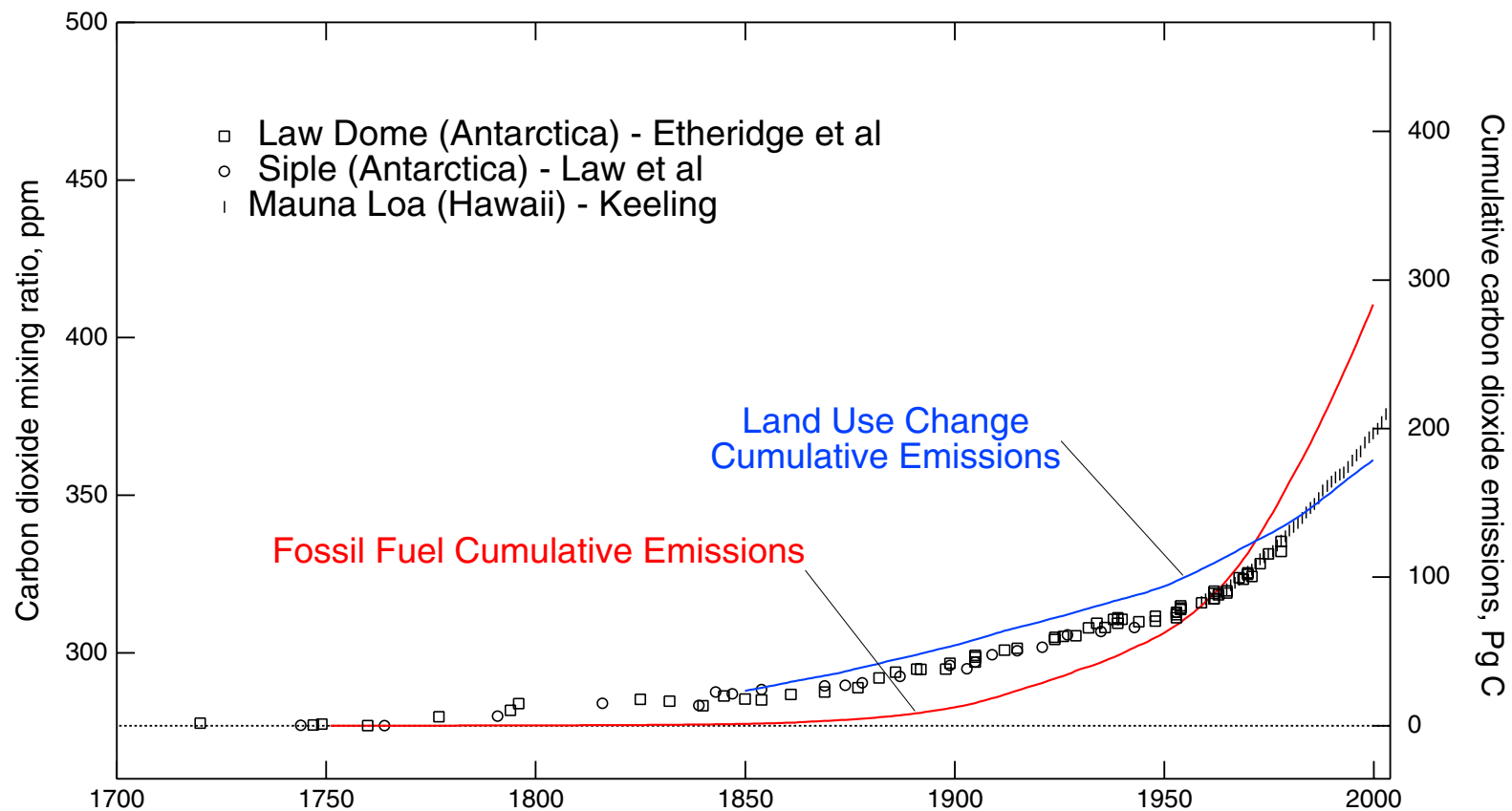
# ATTRIBUTION OF INCREASE IN ATMOSPHERIC CO<sub>2</sub>

Comparison of *cumulative* CO<sub>2</sub> emissions from fossil fuel combustion with measured increases in atmospheric CO<sub>2</sub>.



# ATTRIBUTION OF INCREASE IN ATMOSPHERIC CO<sub>2</sub>

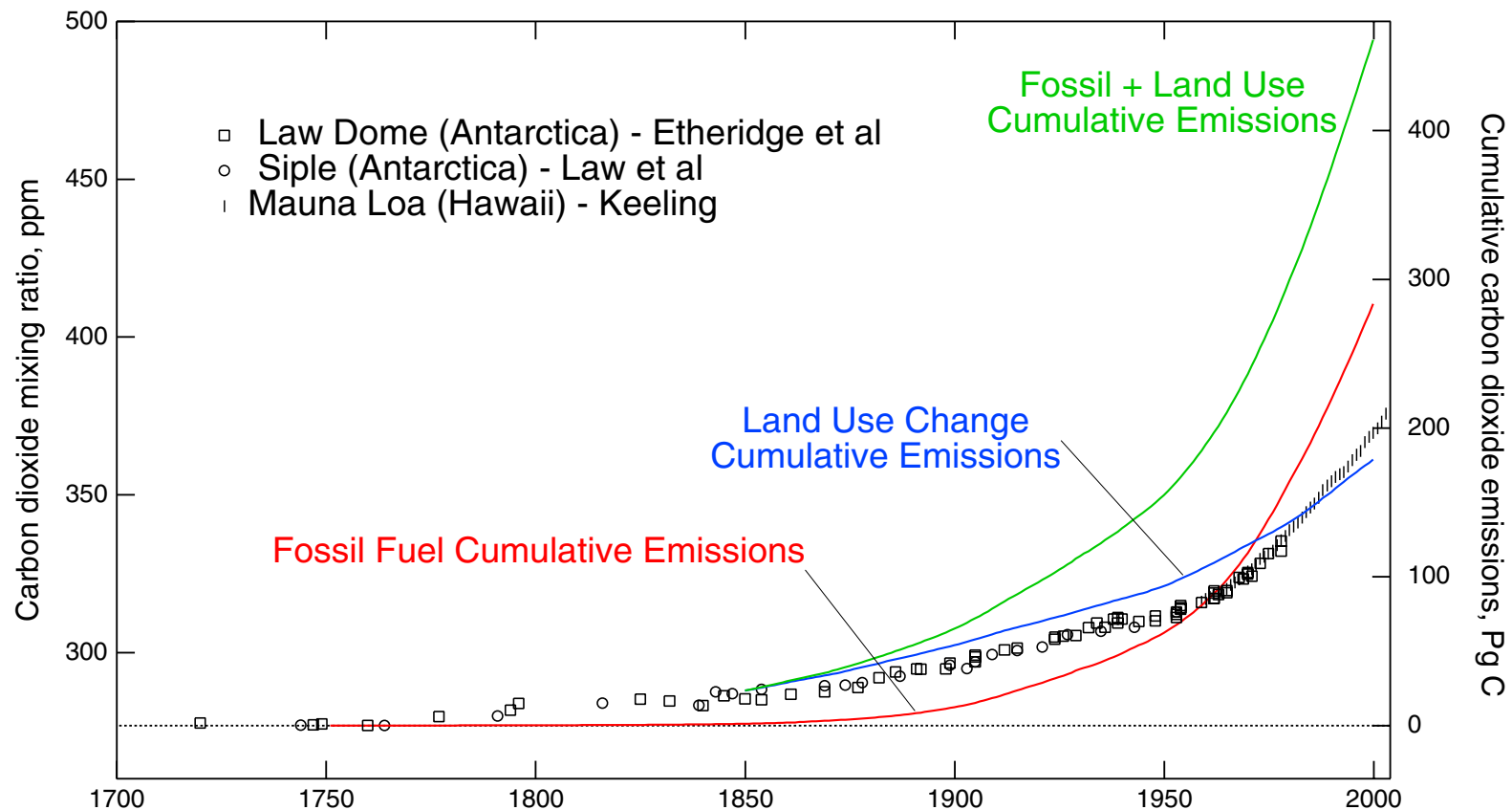
Comparison of *cumulative* CO<sub>2</sub> emissions from fossil fuel combustion and land use changes with measured increases in atmospheric CO<sub>2</sub>.





# ATTRIBUTION OF INCREASE IN ATMOSPHERIC CO<sub>2</sub>

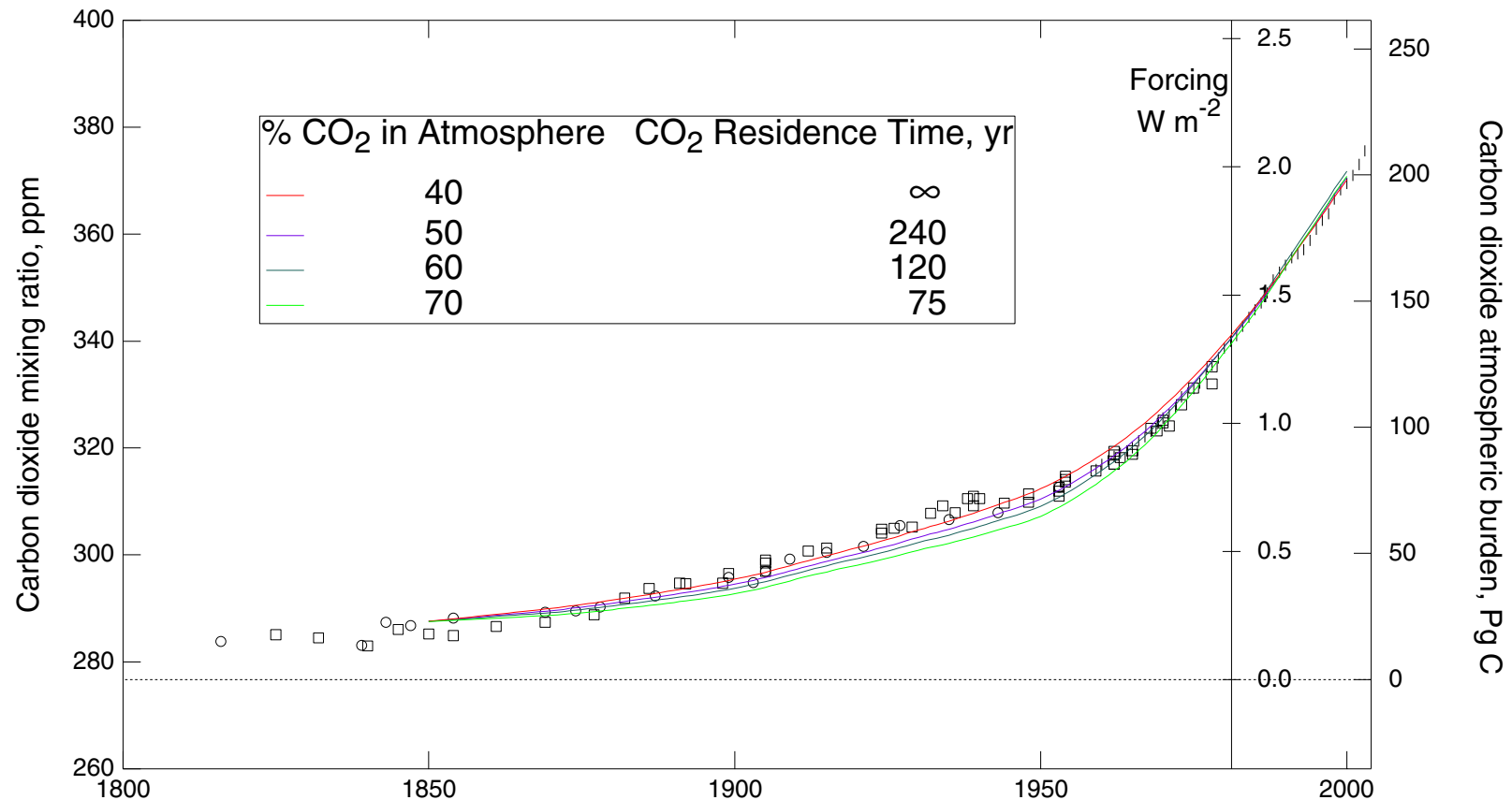
Comparison of *cumulative* CO<sub>2</sub> emissions from fossil fuel combustion and land use changes with measured increases in atmospheric CO<sub>2</sub>.



*Prior to 1970* the increase in atmospheric CO<sub>2</sub> was dominated by emissions from land use changes, not fossil fuel combustion.

# ATTRIBUTION OF ATMOSPHERIC CO<sub>2</sub>

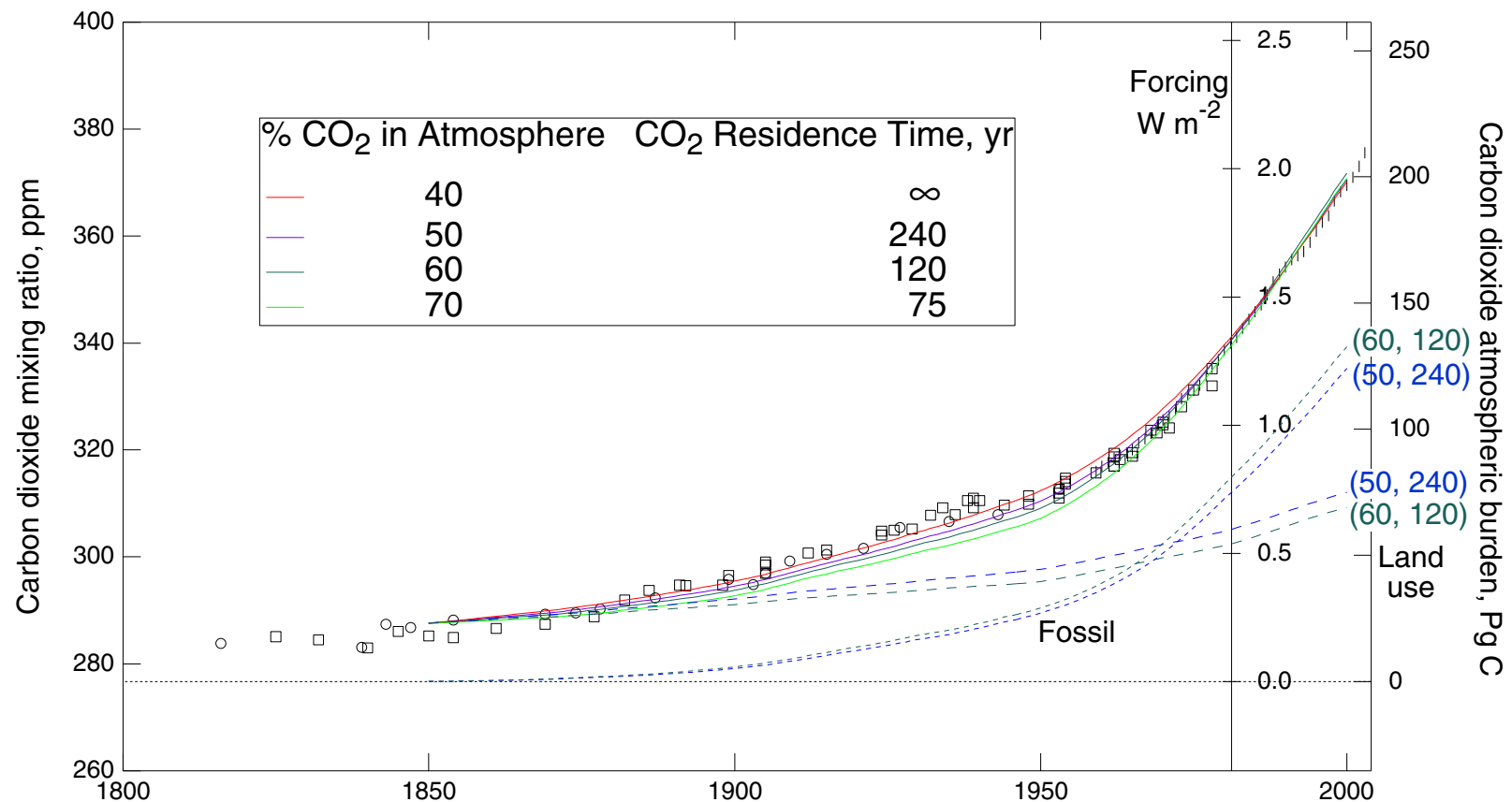
Comparison of CO<sub>2</sub> *mixing ratio and forcing* from fossil fuel combustion and land use changes



Partition-decay model: 
$$\frac{d\Delta\text{CO}_2}{dt} = f_A Q - \Delta\text{CO}_2 e^{-t/\tau}$$

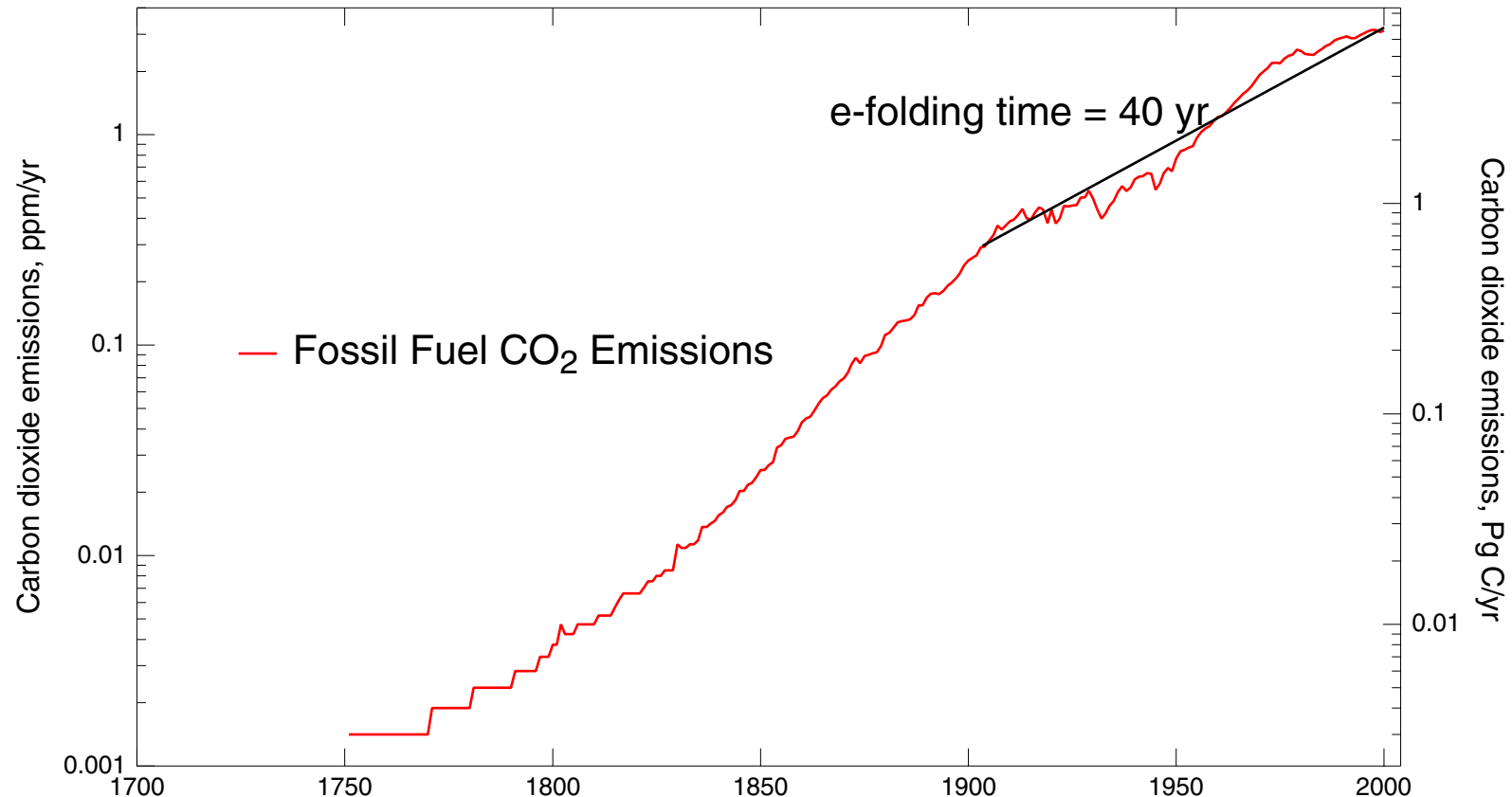
# ATTRIBUTION OF ATMOSPHERIC CO<sub>2</sub>

Comparison of CO<sub>2</sub> *mixing ratio and forcing* from fossil fuel combustion and land use changes



CO<sub>2</sub> from land use emissions – *not fossil fuel combustion* – has been the dominant contribution to atmospheric CO<sub>2</sub> and forcing over the last century. *This conclusion is not sensitive to the parameters.*

# INCREASE OF CO<sub>2</sub> EMISSIONS IS ROUGHLY EXPONENTIAL



The time constant for emissions growth is well less than time constant for decrease of excess CO<sub>2</sub>.

The mean age of fossil fuel CO<sub>2</sub> in the atmosphere is ~ 40 years.

The climate influence of excess fossil fuel CO<sub>2</sub> already in the atmosphere will continue well into the future.

# OBSERVATIONS ABOUT CO<sub>2</sub>

The residence time of excess atmospheric CO<sub>2</sub> is ~100 years.

CO<sub>2</sub> from *land use emissions* was the dominant contribution to excess CO<sub>2</sub> and its climate forcing over the last century.

CO<sub>2</sub> from *fossil fuel combustion* now the dominant contribution to excess CO<sub>2</sub> and its climate forcing.

Fossil fuel CO<sub>2</sub> emissions are increasing with time constant of ~40 years.

Excess CO<sub>2</sub> now in the atmosphere is ~40 years' emissions.

Most of the forcing of present excess CO<sub>2</sub> lies ahead.

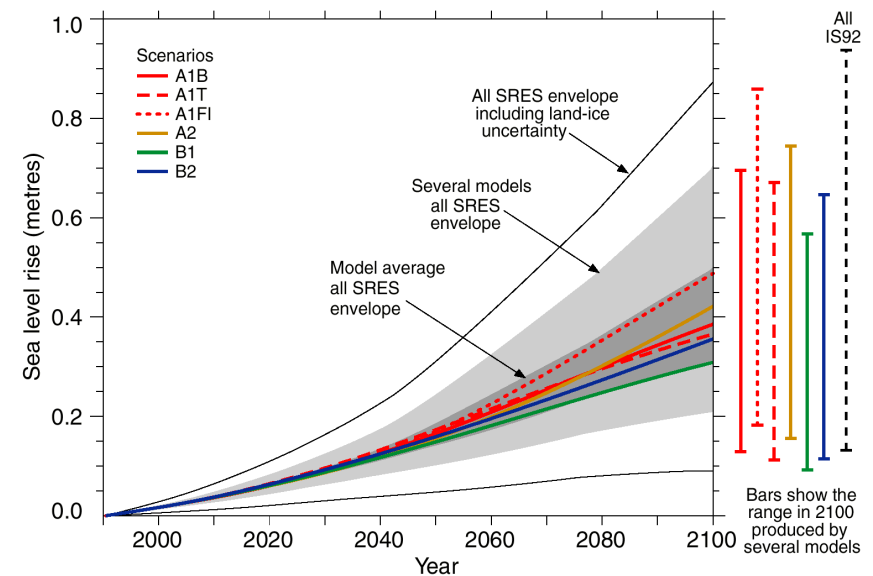
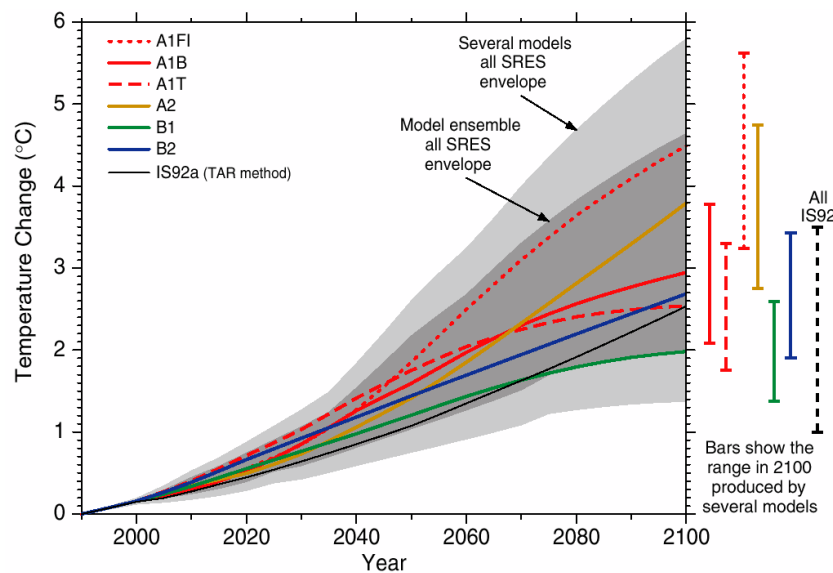
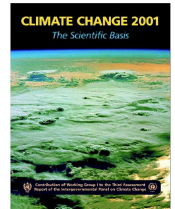
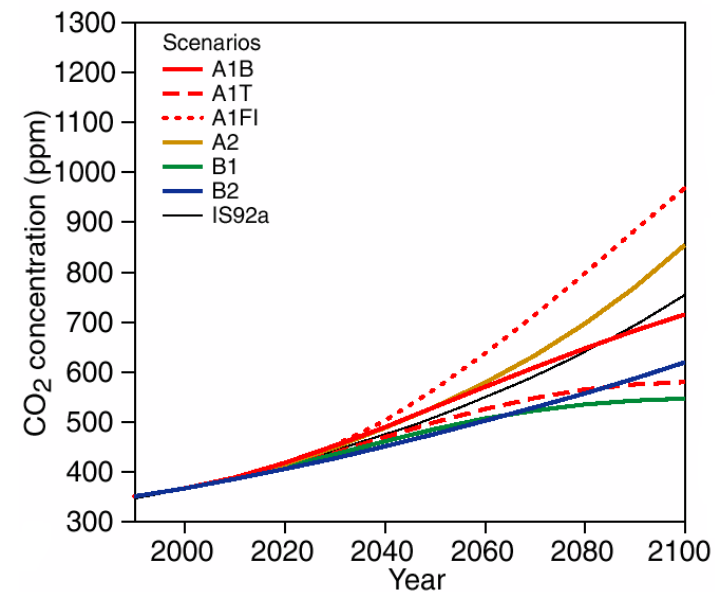
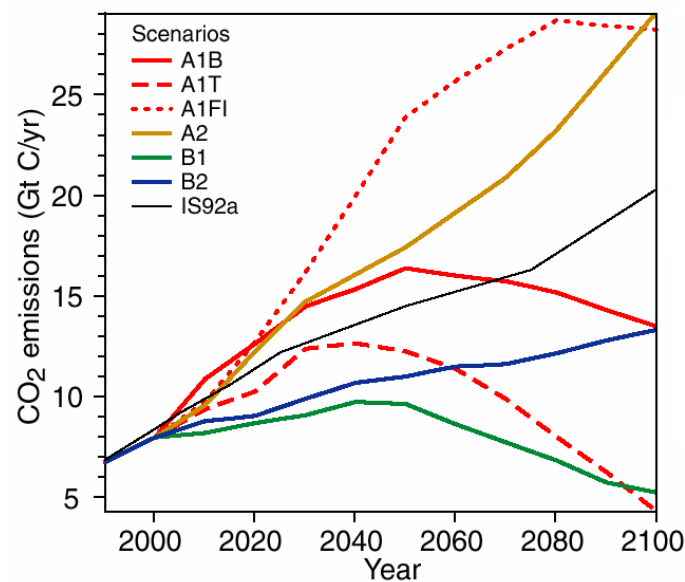
*Looking to the  
Future . . .*



*Prediction is difficult,  
especially about the future.*

*– Niels Bohr*

# PROJECTIONS OF FUTURE CO<sub>2</sub>, TEMPERATURE, AND SEA LEVEL



Contributors to uncertainty in future temperature include *emissions*, *concentrations*, and Earth's *climate sensitivity*.



# ***CLIMATE RESPONSE***

The ***change*** in global and annual mean temperature,  $\Delta T$ , K, resulting from a given radiative forcing.

***Working hypothesis:***

*The change in global mean temperature depends on the magnitude of the forcing, not its nature or its spatial distribution.*

$$\Delta T = \lambda F$$

# ***CLIMATE SENSITIVITY***

The ***change*** in global and annual mean temperature per unit forcing,  $\lambda$ , K/(W m<sup>-2</sup>).

# TOP-LEVEL QUESTION IN CLIMATE CHANGE SCIENCE

- *How much will the global mean temperature change?*

$$\Delta T = \lambda F$$

where  $F$  is the *forcing* and  $\lambda$  is the *climate sensitivity*.

- A *forcing* is a change in a radiative flux component,  $\text{W m}^{-2}$ .
- Forcings are thought to be *additive* and *fungible*.

- *What is Earth's climate sensitivity?*

- *U.S. National Academy Report (Charney, 1979):*  $F = 4 \text{ W m}^{-2}$

“ We estimate the most probable global warming for a doubling of CO<sub>2</sub> to be *near 3 degrees C*, with a probable error of *plus or minus 1.5 degrees*.

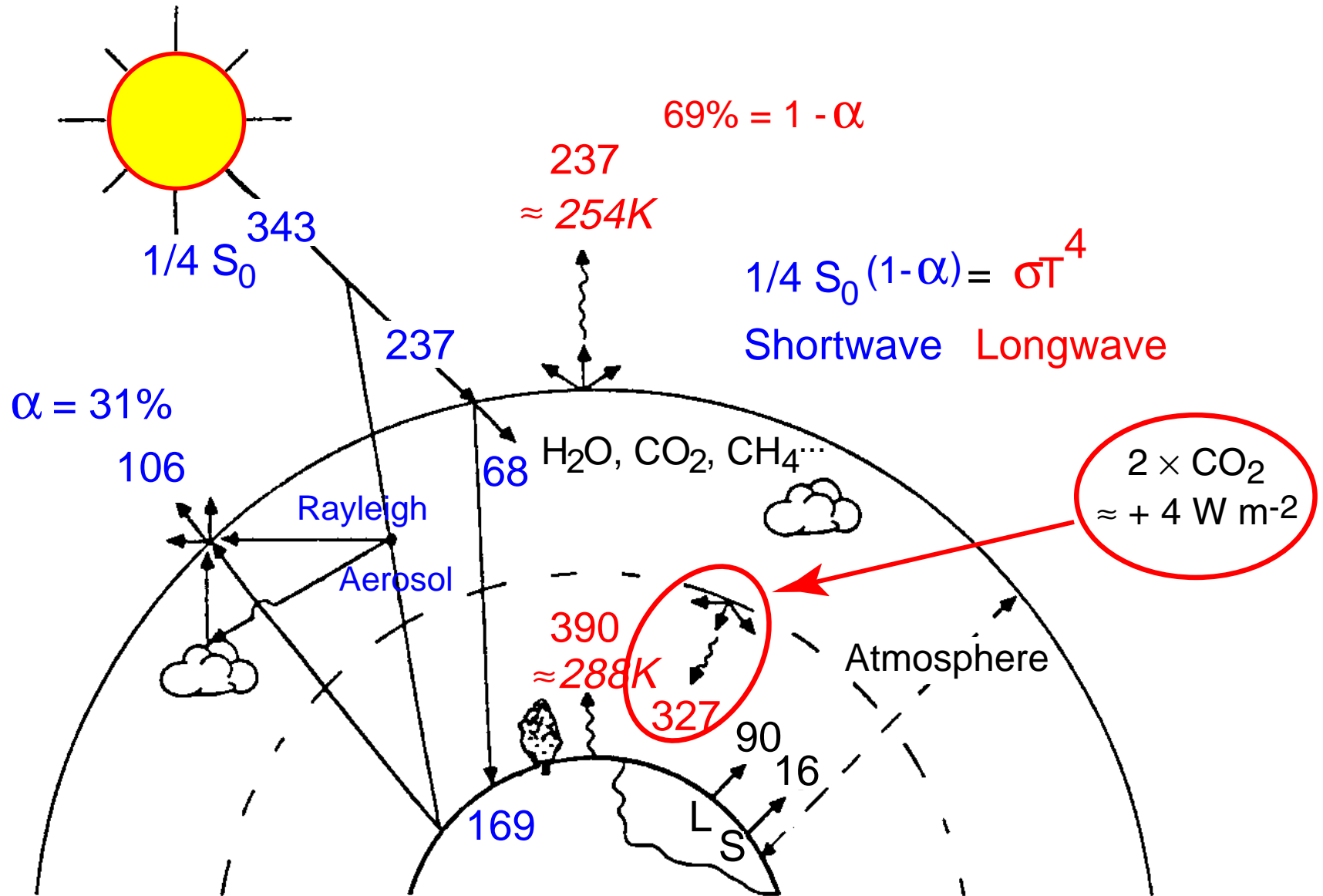
- *Intergovernmental Panel on Climate Change (IPCC, 2001):*

“ Climate sensitivity [to CO<sub>2</sub> doubling] is likely to be in the range *1.5 to 4.5°C*.

*This level of uncertainty is not very useful for policy planning.*

# GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



*Schwartz, 1996, modified from Ramanathan, 1987*

# HOW CAN CLIMATE SENSITIVITY BE DETERMINED?

$$\text{Climate sensitivity } \lambda = \Delta T / F$$

- *Climate models* evaluated by performance on prior climate change, and/or
- *Empirical determination* from prior climate change.
- Either way,  $\Delta T$  and  $F$  must be determined with sufficiently small uncertainty to yield an uncertainty in  $\lambda$  that is useful for informed decision making.

# BILLIARD BALL TEMPERATURE SENSITIVITY

Climate sensitivity evaluated according to the Stefan-Boltzmann radiation law



Dependence of emitted flux on temperature:  $F = \sigma T^4$

Sensitivity of flux with temperature:  $\frac{dF}{dT} = 4\sigma T^3$

Sensitivity of temperature with flux:  $\lambda \equiv \frac{dT}{dF} = (4\sigma T^3)^{-1}$

For  $T = 288$  K (15 °C or 59 °F)  $\lambda = 0.18$  K / (W m<sup>-2</sup>)

# CLIMATE CHANGE SENSITIVITY

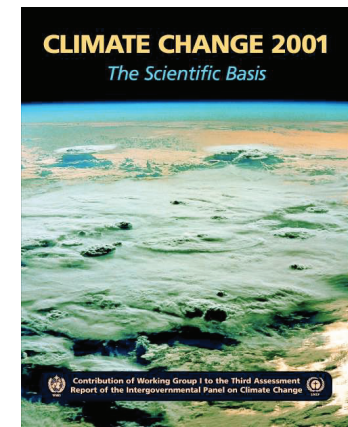
## Summary of 15 Current Climate Models

Quantity, Unit	Mean	Standard Deviation	Range
$\lambda$ , K/(W m <sup>-2</sup> )	0.87	0.23	0.5 - 1.25
$\Delta T_{2\times}$ , K	3.5	0.9	2 - 5

IPCC *Climate Change 2001*, Cambridge University Press, 2001

*Why do climate models exhibit higher sensitivity?*

***Positive Feedback***



# EMPIRICAL CLIMATE SENSITIVITY

Greenhouse forcing over the industrial period is  $2.5 \text{ W m}^{-2}$

Temperature increase over the industrial period is  $0.6 \text{ K}$ .

Empirical Sensitivity:

$$\lambda = \frac{dT}{dF} = \frac{0.6 \text{ K}}{2.5 \text{ W m}^{-2}} = \boxed{0.24 \text{ K / (W m}^{-2}\text{)}} \quad \text{or} \quad \Delta T_{2\times} = 1 \text{ K}$$

*Why is this estimate so low?*

*Thermal lag of climate system?*

*Other forcings?*

# TIME CONSTANTS OF EARTH'S CLIMATE SYSTEM

Consider a perturbation to the climate system

How long does it take for the system to adjust to the new state?

There are many time constants:

*Minutes*. It gets cooler when the sun goes “behind a cloud.”

*Hours*. It is cooler at night than during the day; but there is a lag.

*Months*. It is colder in winter than in summer, but there is a lag.

*Years*. Thermal buffering of the ocean mixed layer.

*Thousands of years*. The deep oceans.

*Millions of years*. Thermal mass of the whole planet (Kelvin and the age of Earth)



# TIME CONSTANT OF EARTH'S CLIMATE SYSTEM BASED ON THE OCEAN MIXED LAYER

For the heat content of the climate system given by

$$\frac{dH}{dt} = J_{\text{in}} - \sigma T^4$$

the relaxation time constant for a perturbation from an initial temperature  $T_0$  is

$$\tau = \frac{CT_0}{4J_0}$$

where  $C$  is the heat capacity of the system.

# HEAT CAPACITY OF THE SYSTEM

***Lemma:*** the heat capacity of the atmosphere  $\ll$  the heat capacity of the ocean mixed layer.

The mass of the atmosphere = the mass of the first 10 m of water.

The heat capacity of the atmosphere = the heat capacity of the first 2.5 m of water.

The depth of the ocean mixed layer  $\approx 100$  m, so the heat capacity of the atmosphere  $\approx 1/40$  that of the ocean mixed layer.

So just consider the heat capacity of the ocean mixed layer

For  $z_{ml} = 100$  m, the heat capacity of the system is

$$C = c_w \rho_w z_{ml} = 4.19 \times 10^8 \text{ J m}^{-2}$$

# TIME CONSTANT OF THE CLIMATE SYSTEM

$$\text{For } z_{\text{ml}} = 100 \text{ m, } \tau = \frac{CT_0}{4J_0} = \frac{c_w \rho_w z_{\text{ml}} T_0}{4J_0} = 4 \text{ years.}$$

[This does not take into account any flux of excess heat into the deep ocean or solid earth.]

Climate response is essentially instantaneous.

This justifies inferring climate sensitivity from forcing and temperature response.

We need consider only instantaneous forcing, not integrated forcing.

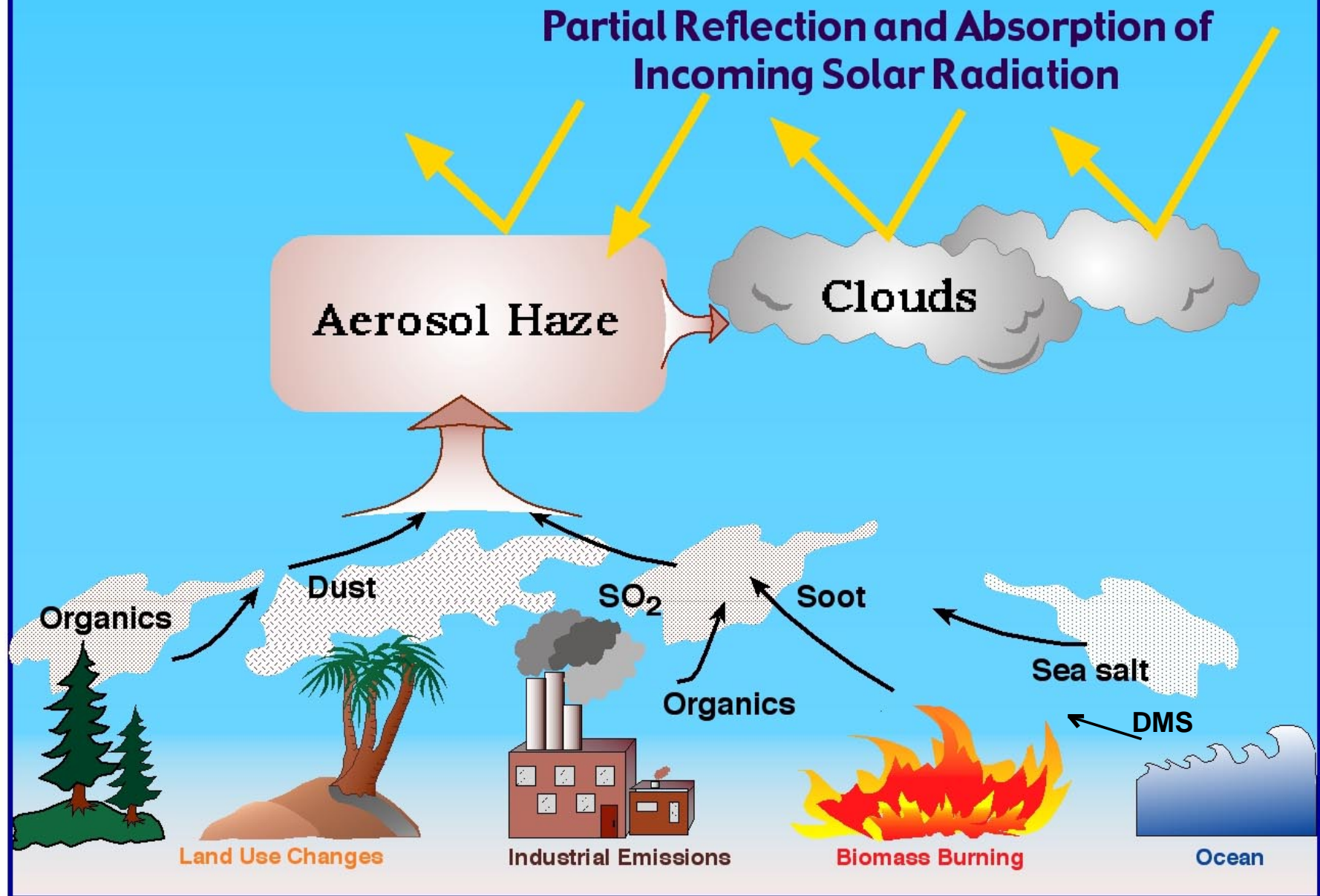
***This is a very forgiving result!***

The warming due to excess CO<sub>2</sub> will diminish as the excess CO<sub>2</sub> decays.

WHAT'S MISSING FROM THIS STORY?

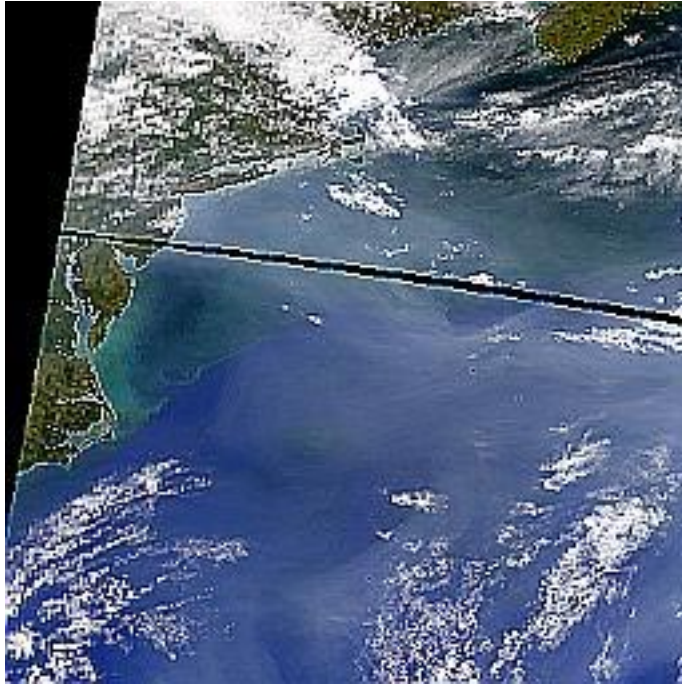
***RADIATIVE FORCING  
BY AEROSOLS***

# Radiative Forcing by Tropospheric Aerosol

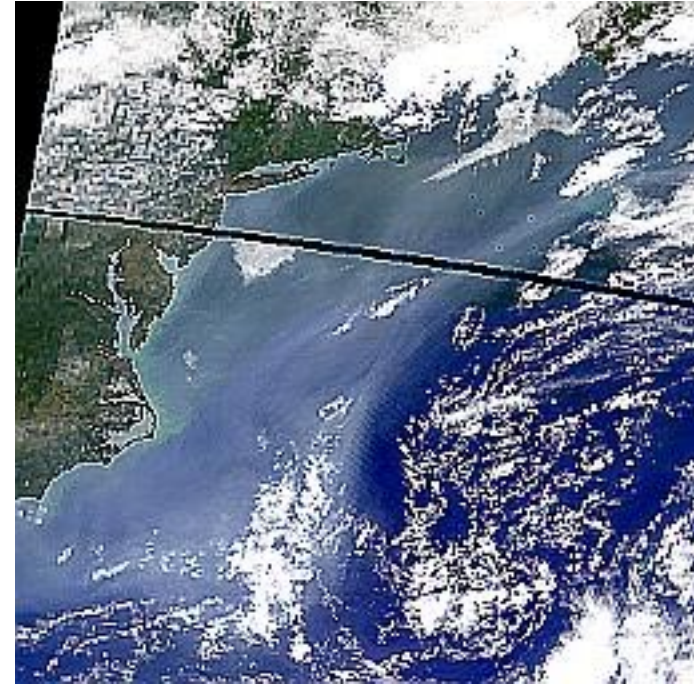




# LIGHT SCATTERING BY ANTHROPOGENIC AEROSOLS, 2000



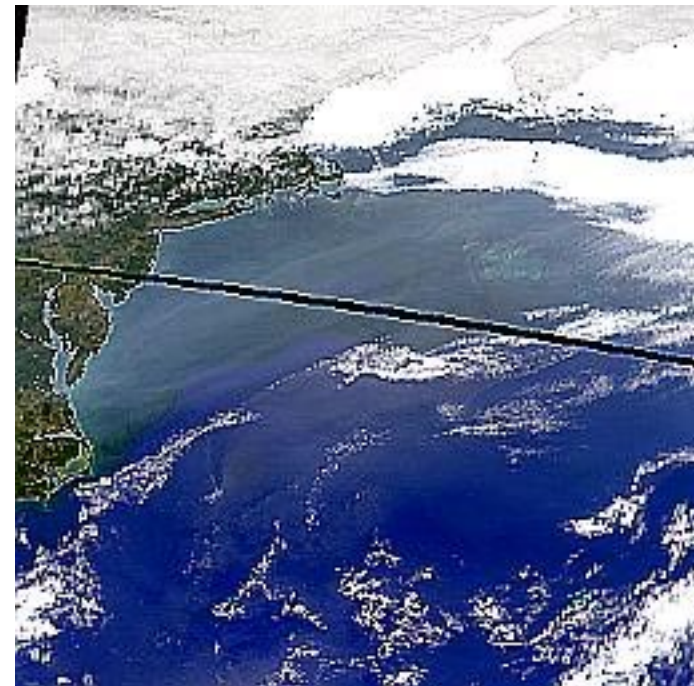
May 8



June 2



June 3



June 11

# AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

## *Direct Effect (Cloud-free sky)*

Light scattering -- Cooling influence

Light absorption -- Warming influence, depending on surface

## *Indirect Effects (Aerosols influence cloud properties)*

More droplets -- Brighter clouds (Twomey)

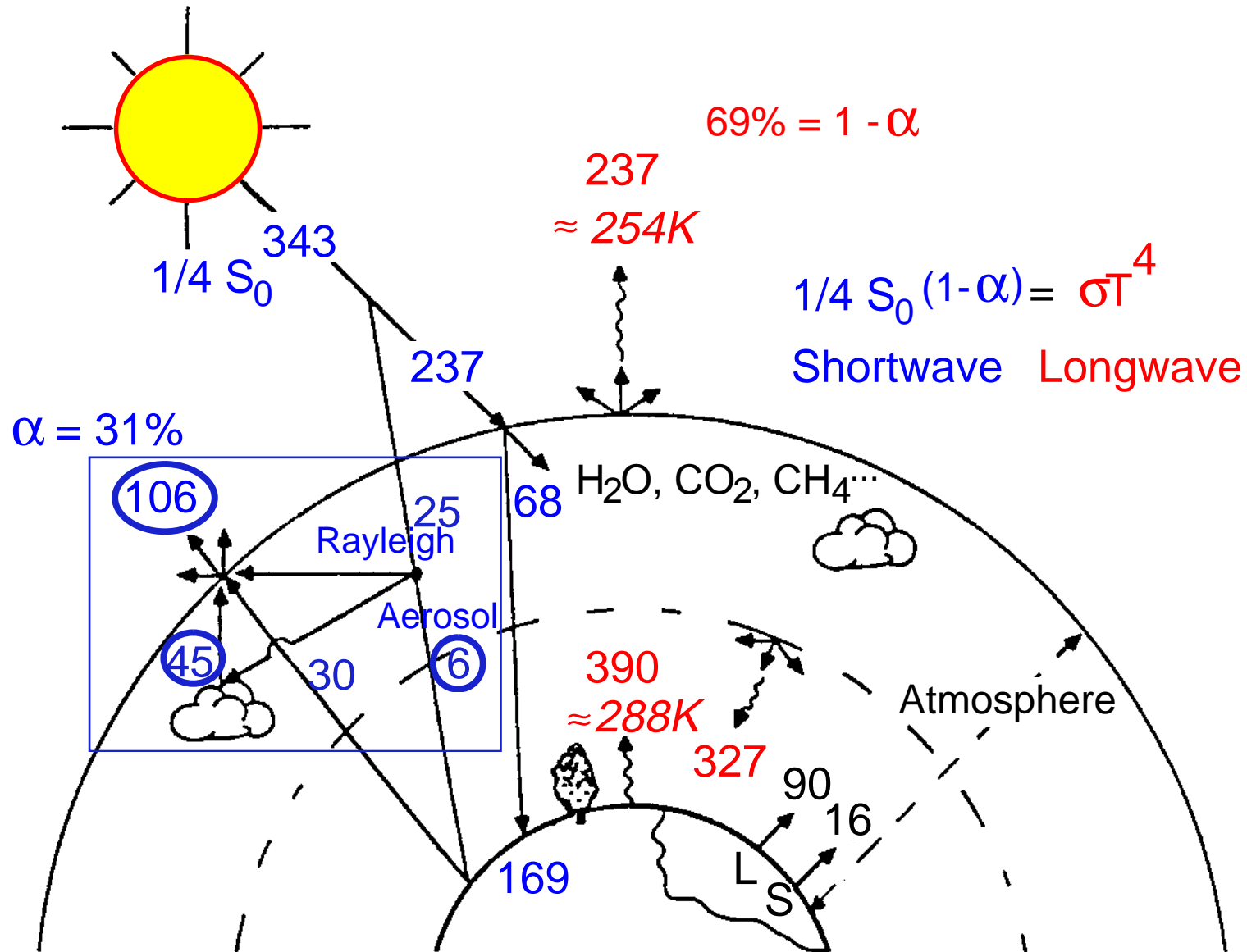
More droplets -- Enhanced cloud lifetime (Albrecht)

## *Semi-Direct Effect*

Absorbing aerosol heats air and evaporates clouds

# GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



*Modified from Ramanathan, 1987*



# ELEMENTS OF AEROSOL FORCING

Forcing depends on *amount of material* present and on aerosol *microphysical and optical properties* (size, single scattering albedo, ability to nucleate cloud drops).

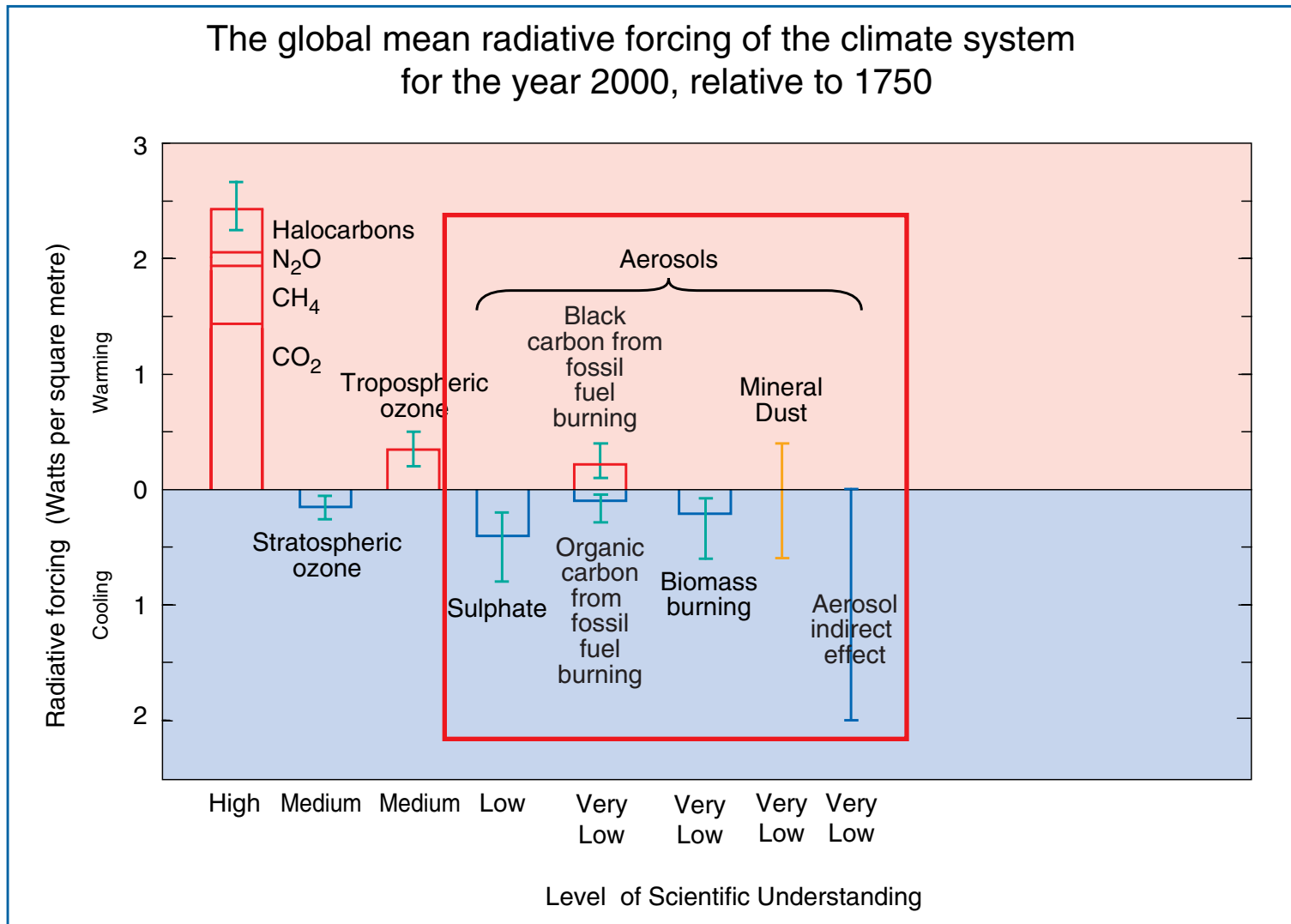
Amount of material present depends on *emissions, atmospheric chemistry*, and *removal*.

Anthropogenic emissions are associated largely with *fossil fuel combustion* (sulfate, soot, secondary organics), *biomass burning* (organics and soot), *mineral dust* from disturbed soils.

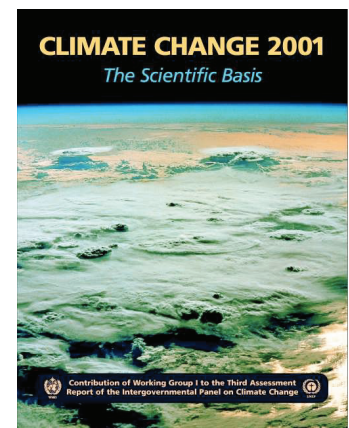
Removal occurs mainly by precipitation with *residence time of about a week*.

# RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD IPCC (2001)

GHG's and aerosol direct and indirect effects



Summary for Policymakers A Report of Working Group I of the Intergovernmental Panel on Climate Change



# WHY SO LARGE UNCERTAINTY IN AEROSOL FORCING?

- *Uncertainties in knowledge of atmospheric composition*

*Mass loading and chemical and microphysical properties and cloud nucleating properties of anthropogenic aerosols, and geographical distribution.*

*At present and as a function of secular time.*

- *Uncertainties in knowledge of atmospheric physics of aerosols*

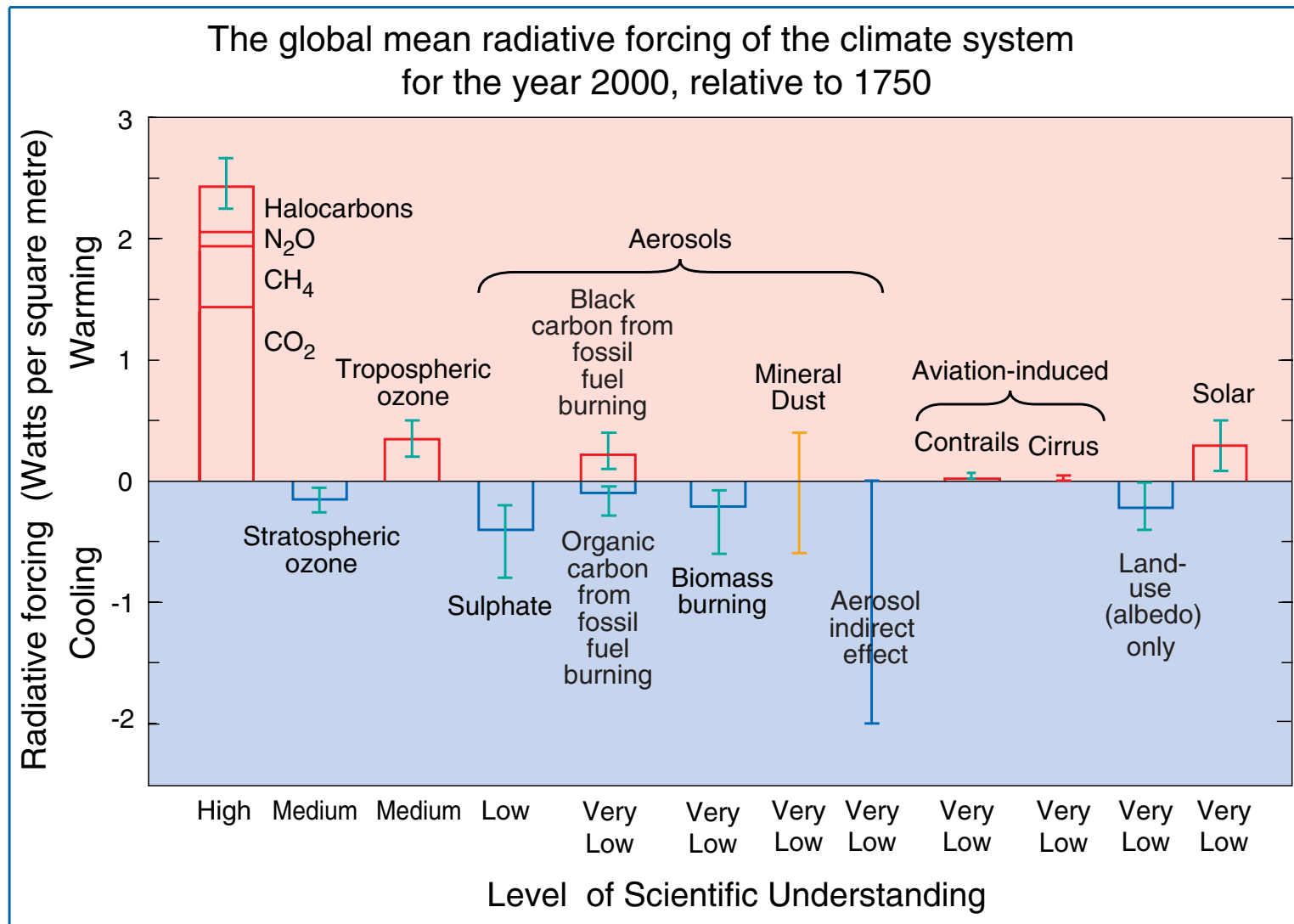
*Relating direct radiative forcing and cloud modification by aerosols to their loading and their chemical and microphysical properties.*

*The U.S. Department of Energy has initiated a new research program examining aerosol chemistry and physics pertinent to radiative forcing of climate change.*

# **ADDING UP THE FORCINGS**

# RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD

## IPCC (2001)



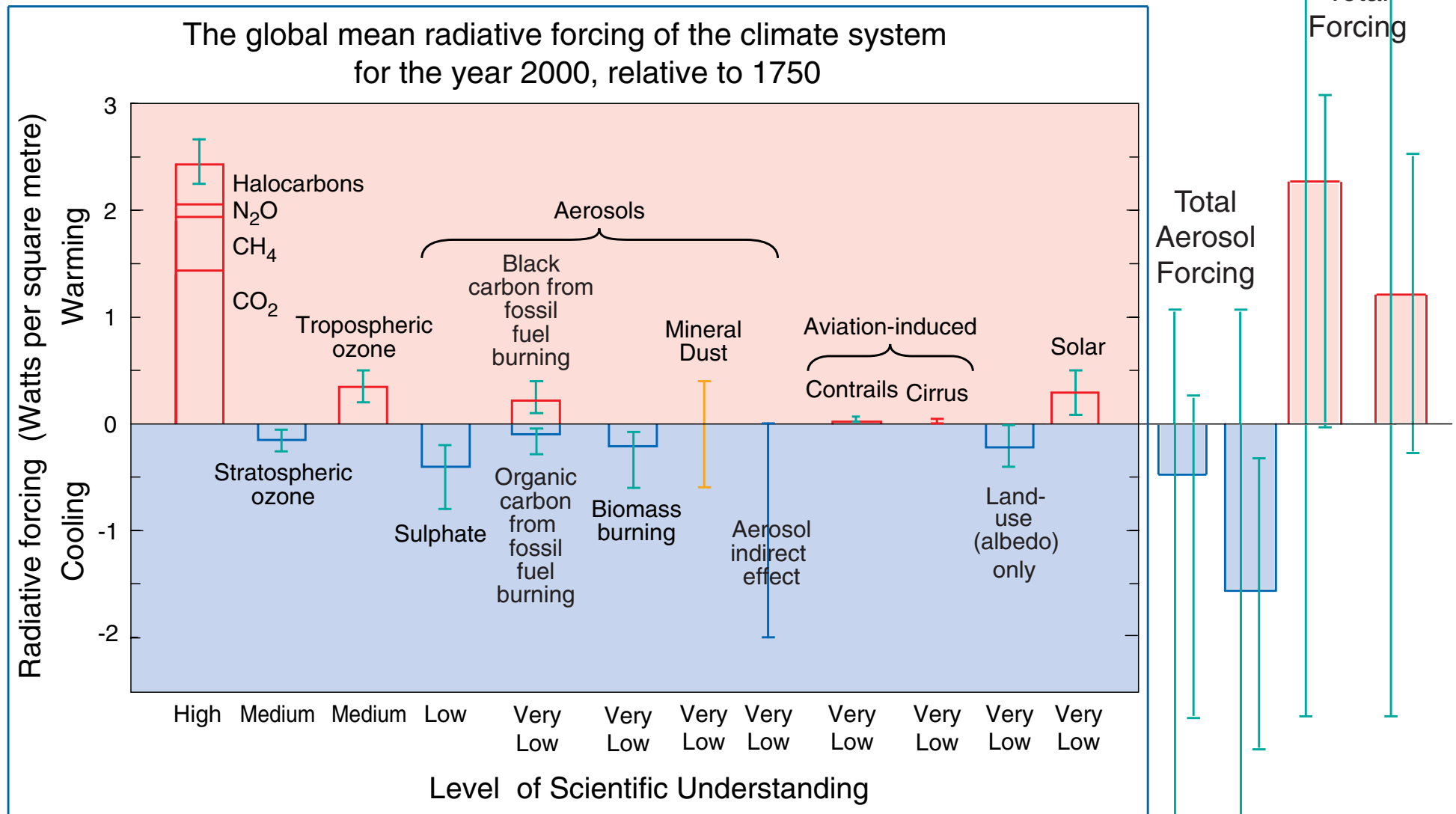
Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

# RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD

## IPCC (2001)

With total aerosol forcing and total forcing and uncertainties



Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

# IMPLICATIONS OF AEROSOL FORCING

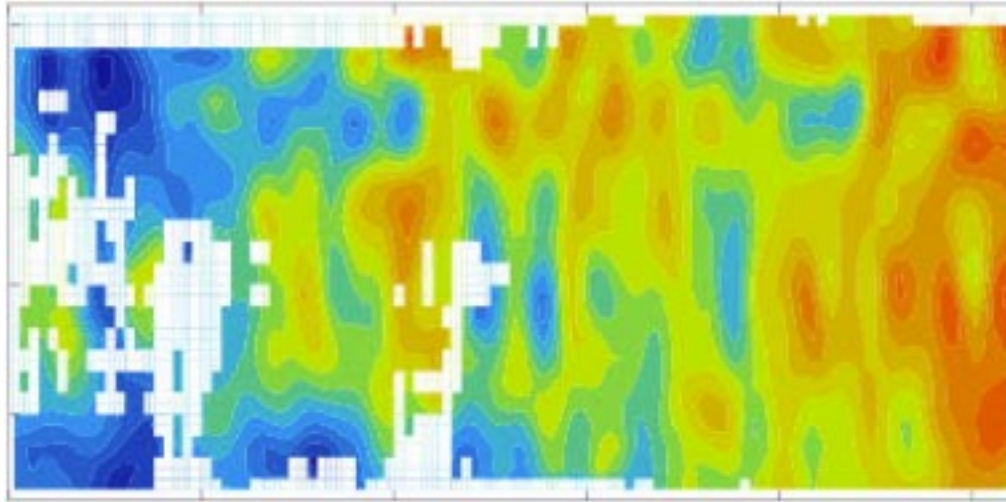
- Aerosol negative (cooling) forcing is likely *offsetting* a substantial fraction of positive (warming) forcing by greenhouse gases.
- A substantial fraction of the forcing of 40 years of CO<sub>2</sub> emissions is being offset by *a week's worth of aerosol*.
- The aerosol forcing is likely responsible for the *low apparent climate sensitivity* based on greenhouse gas forcing only.
- It is very likely that the global warming due to CO<sub>2</sub> and other GHG's is *substantially greater* than has been experienced thus far.
- The uncertainty in aerosol forcing and the resultant uncertainty in total forcing over the industrial period are so great as to *preclude meaningful empirical inference of climate sensitivity and evaluation of climate models*.

# SOME CONCLUDING OBSERVATIONS

- GHG concentrations and forcing are increasing. GHGs persist in the atmosphere for decades to centuries.
- Global mean temperature trends and other indicia point to a warming world.
- Aerosol forcing is comparable to GHG forcing but much more uncertain. Aerosols are short-lived in the atmosphere.
- The sensitivity of the climate system is highly uncertain but is almost certainly substantially greater than is inferred based on GHG forcing alone.
- Decisions on GHG policy must be made in an uncertain world. Lack of controls on GHG emissions is also a decision.



# DOING SOMETHING ABOUT THE CLIMATE:



*Thank you*

<http://www.ecd.bnl.gov/steve/schwartz.html>